

# **Decadal Survey CLARREO Mission**

Jim Anderson  
Harvard University

CLARREO Workshop  
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University of Maryland Inn and Conference Center  
Adelphi, MD

# Earth Science and Applications from Space

## *National Imperatives for the Next Decade and Beyond*



AMS Town Hall 1/15/07

Prepublication: <http://www.nap.edu/catalog/11820.html>

# ESAS Charge

- Recommend a prioritized list of flight missions and supporting activities to support national needs for research and monitoring of the dynamic Earth system during the next decade.
- Identify important directions that should influence planning for the decade beyond.

*Sponsors: NASA SMD, NOAA NESDIS,  
USGS Geography*

# Overarching Recommendation

The U.S. government, working in concert with the private sector, academe, the public, and its international partners, should renew its investment in Earth observing systems and restore its leadership in Earth science and applications.

# Final Report

- Recommends a path forward that restores U.S. leadership in Earth science and applications and averts the potential collapse of the system of environmental satellites
- Presents an integrated suite of missions
  - Panel recommendations rolled-up
  - Missions sequenced
  - Overall cost matched to anticipated resources plus reasonable growth
- Highest priorities of each panel preserved
- Some guidance on how to handle budget or technology development problems

Committee found that fundamental improvements were needed to establish a disciplined structure linking:

- *Decision processes that serve societal objectives*
- *The analyses, forecasts and models that provide timely and coherent input to those decision processes, and*
- *Observations selected to test and systematically improve those forecasts*

# Strategic Choices Driven by Society's Need for Decision Structures

## Decision Structures in Service to Society for:

- Climate Policy
- Energy Policy
- Human health
- Water resources
- Weather and severe storms
- Solid Earth hazards
- Land use, Ecosystems, Biodiversity

## Required Forecasts:

- Rate of Sea Level Rise
- Airborne and water borne toxicity
- Rainfall, river flow, ground water, snow pack
- Regional temperatures, hurricane intensity, optical properties of atmosphere
- Earthquakes, volcanoes, tsunamis

## Critical Observations to Specifically Test Forecast Credibility

- Nitrate, sulfate, organics, heavy metal effluents globally
- Index of refraction, absolute spectrally resolved radiance, solar irradiance
- Surface deformation

# The National Strategy: Program in the Earth sciences that will balance

- *Economic competitiveness*
- *Protection of life and property*
- *Stewardship of the planet for this and future generations*

Taking responsibility for developing and connecting these elements in service to society

- *Represents a new social contract for the scientific community*
- *The scientific community must focus on meeting the demands of society explicitly – in addition to satisfying its curiosity concerning how the Earth system works*

# Prioritization Process

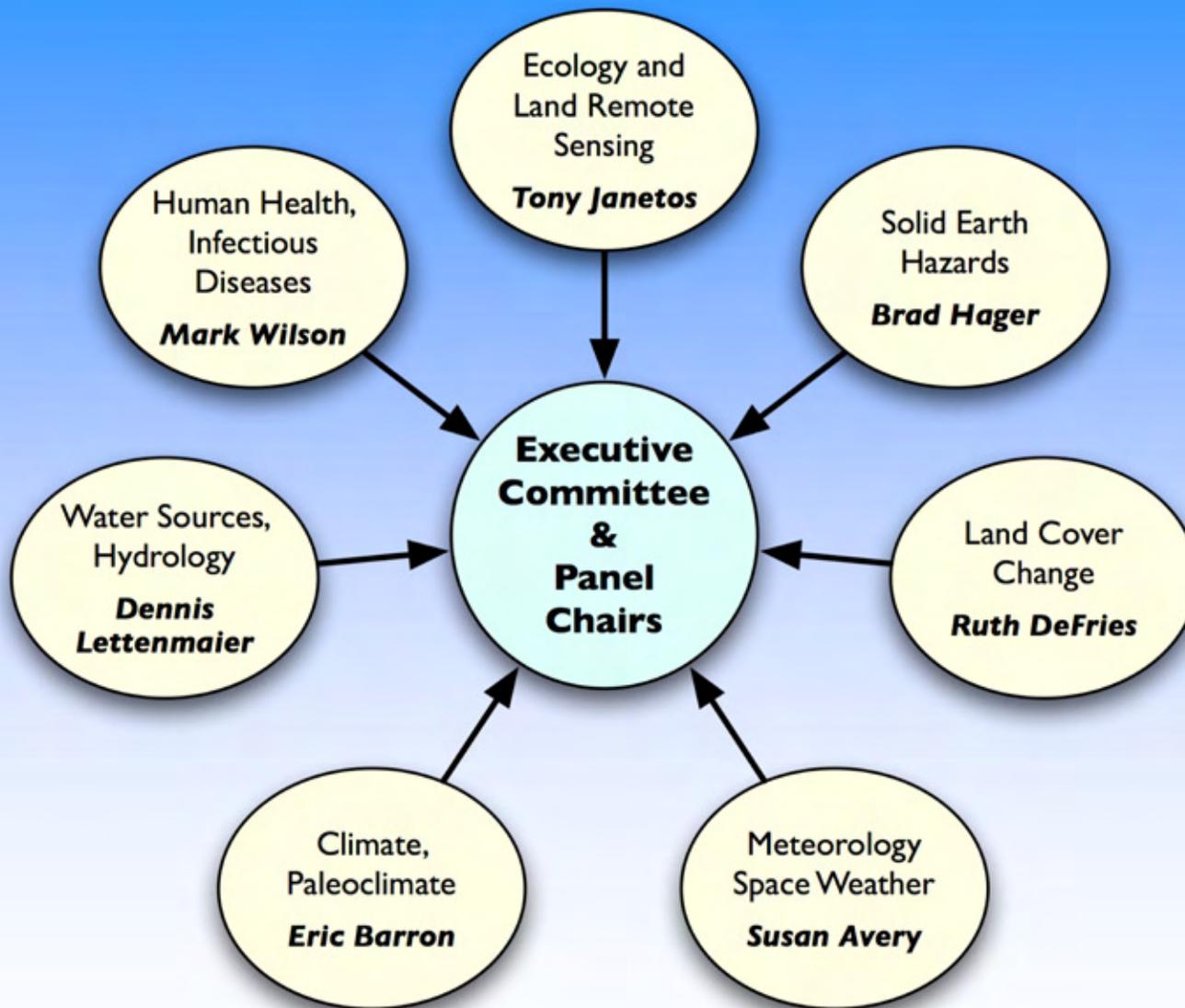
The prioritization process for mission selection involved eight criteria used to set relative rankings:

1. Contribution to the most important scientific questions facing Earth sciences today (scientific merit, discovery, exploration)
2. Contribution to applications and policy making (societal benefits)
3. Contribution to long-term observational record of the Earth
4. Ability to complement other observational systems, including national and international plans
5. Affordability (cost consideration, either total costs for mission or costs per year)
6. Degree of readiness (technical, resources, people)
7. Risk mitigation and strategic redundancy (backup of other critical systems)
8. Significant contribution to more than one thematic application or scientific discipline

# NRC Decadal Study Structure

The study was organized with an executive (steering) committee overseeing the work of thematically-organized study panels:

1. Earth science applications and societal needs
2. Land-use change, ecosystem dynamics, and biodiversity
3. Weather (including space weather and chemical weather)
4. Climate variability and change
5. Water resources and the global hydrologic cycle
6. Human health and security
7. Solid-Earth hazards, resources, and dynamics



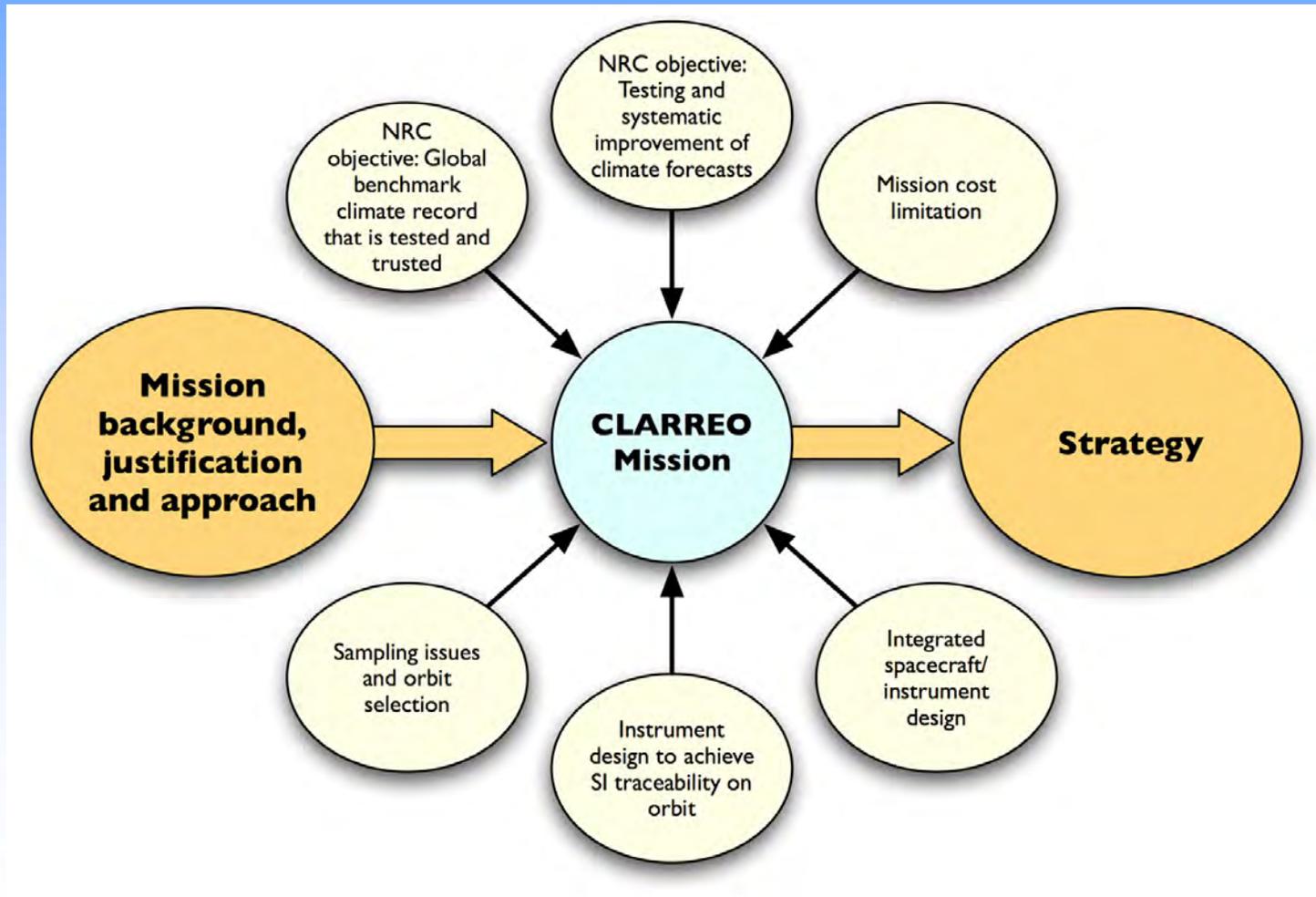
# CLARREO addresses three key Societal Objectives

1. The essential responsibility to present and future generations to put in place a benchmark climate record that is global, accurate in perpetuity, tested against independent strategies that reveal systematic errors, and pinned to international standards
2. The development of an operational climate forecast that is tested and trusted through a disciplined strategy using state-of-the-art observations with mathematically rigorous techniques to systematically improve those forecasts to establish credibility
3. Disciplined decision structure that assimilates accurate data and forecasts into intelligible and specific products that promote international commerce as well as societal stability and security

# Mission and Payload

- The mission is built upon three satellites, each of which requires a specific orbit, and each of which includes an occultation GNSS receiver. In the first category of climate benchmark radiance measurements, two of the satellites contain redundant interferometers that have a spectral resolution of  $1 \text{ cm}^{-1}$ , and encompass the thermal infrared from  $200$  to  $2000 \text{ cm}^{-1}$ , are in true  $90^\circ$  polar orbits to provide a full scan of the diurnal harmonics as well as high latitude coverage from low Earth orbit,
- The components of the CLARREO mission include (1) two small satellites to obtain absolute, spectrally resolved radiance in the thermal IR and a GPS receiver; (2) a third small satellite to continue the IR absolute spectrally resolved radiance measurements but with the addition of benchmark observations to obtain the reflected solar irradiance and a GPS receiver; and (3) re-flight of the incident solar irradiance and CERES broadband instruments on NPP and NPOESS

# Structure of CLARREO Presentation





- Harvard University
  - Jim Anderson
  - John Dykema
  - Stephen Leroy
  - Jonathan Gero
  - Richard Goody
  - Joe Demusz
  - Norton Allen
- University of Wisconsin
  - Hank Revercomb
  - Robert Holz
  - Bob Knuteson
  - Dave Tobin
  - Fred Best
  - Joe Taylor
- University of Maryland
  - Dan Kirk-Davidoff
  - Renu Joseph
- NIST
  - Joe Rice
  - Carol Johnson
  - Jerry Fraser
  - Raju Datla
- Southwest Research Institute
  - Bill Gibson
  - Randy Rose
  - Kelly Smith
- NASA

# NRC Objective: Global Benchmark Climate Record

Benchmark Observations: What are they?

The NRC Decadal Survey recognized that ***when the global climate record emerges as a significant contributor to public policy (societal) decisions, that record will be attacked relentlessly.*** If the climate record cannot stand up to those attacks, the record cannot effectively serve society. Recognition of this led to the requirement that the design of climate observing and monitoring systems from space must ensure the establishment of global, long-term climate records, which are of *high accuracy*, tested for systematic errors on-orbit, and tied to irrefutable standards such as those maintained in the U.S. by the National Institute of Standards and Technology



The magnitude and impact of climate change are not, at present, clearly defined. We do not presently observe Earth's climate system with sufficient accuracy to establish a climate record that is tested and trusted, nor are climate observations in place that can adequately constrain climate model predictions.

### Important Sub-Fields Related to High Accuracy Long-Term Climate Records

| <i>Metrology</i>   | <i>Instrument Systems for High Accuracy Observations from Space</i>  | <i>Climate Community and Climate Records</i>   |
|--|--|--|
| <ul style="list-style-type: none"> <li>• SI traceable standards</li> <li>• Technology and strategy for establishing absolute scales</li> <li>• Innovation for detection of systematic errors</li> <li>• Atomic clocks, phase transition cells, frequency stabilized laser</li> </ul> | <ul style="list-style-type: none"> <li>• Accuracy, precision and bias on-orbit</li> <li>• Blackbodies, frequency standards, temperature cells</li> <li>• Quantum cascade lasers, linear detectors, polarization of optical systems in space</li> <li>• Targets for calibration: Moon, stars, etc.</li> </ul> | <ul style="list-style-type: none"> <li>• Ground-based observations</li> <li>• Sondes, GEOSS</li> <li>• Use of weather data for climate</li> <li>• Intercomparison methods between satellites</li> <li>• <i>In situ</i> intercomparisons</li> </ul> |

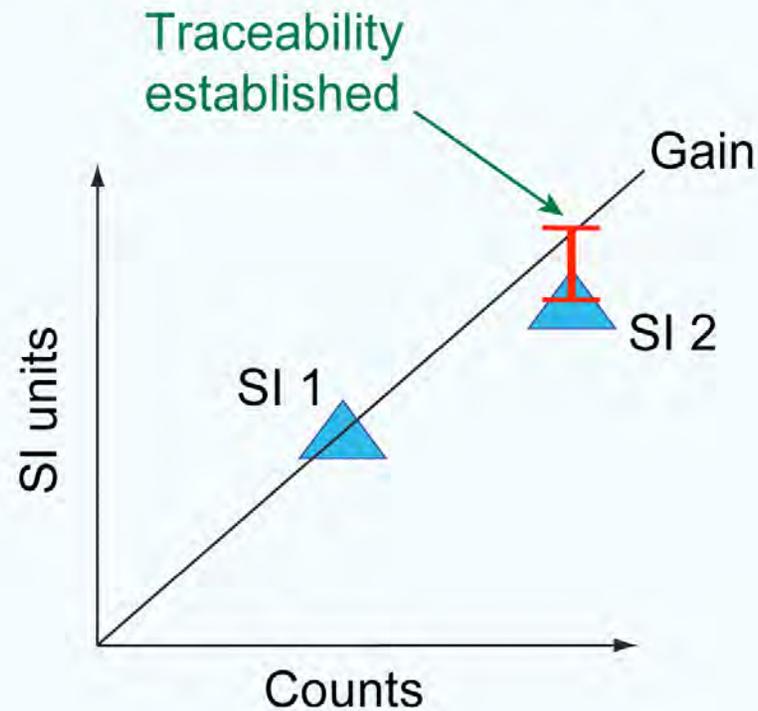
If an observations is not initially SI traceable against an absolute scale, it cannot engage in the logic of testing for systematic error. If an observation cannot independently establish its time dependent bias against an SI traceable standard throughout its observing lifetime, it cannot, by the logic of metrology, provide independent evidence of trends in the climate record---it therefore ceases to constitute a climate benchmark.

# Some Guiding Principles for Satellite Climate Observations

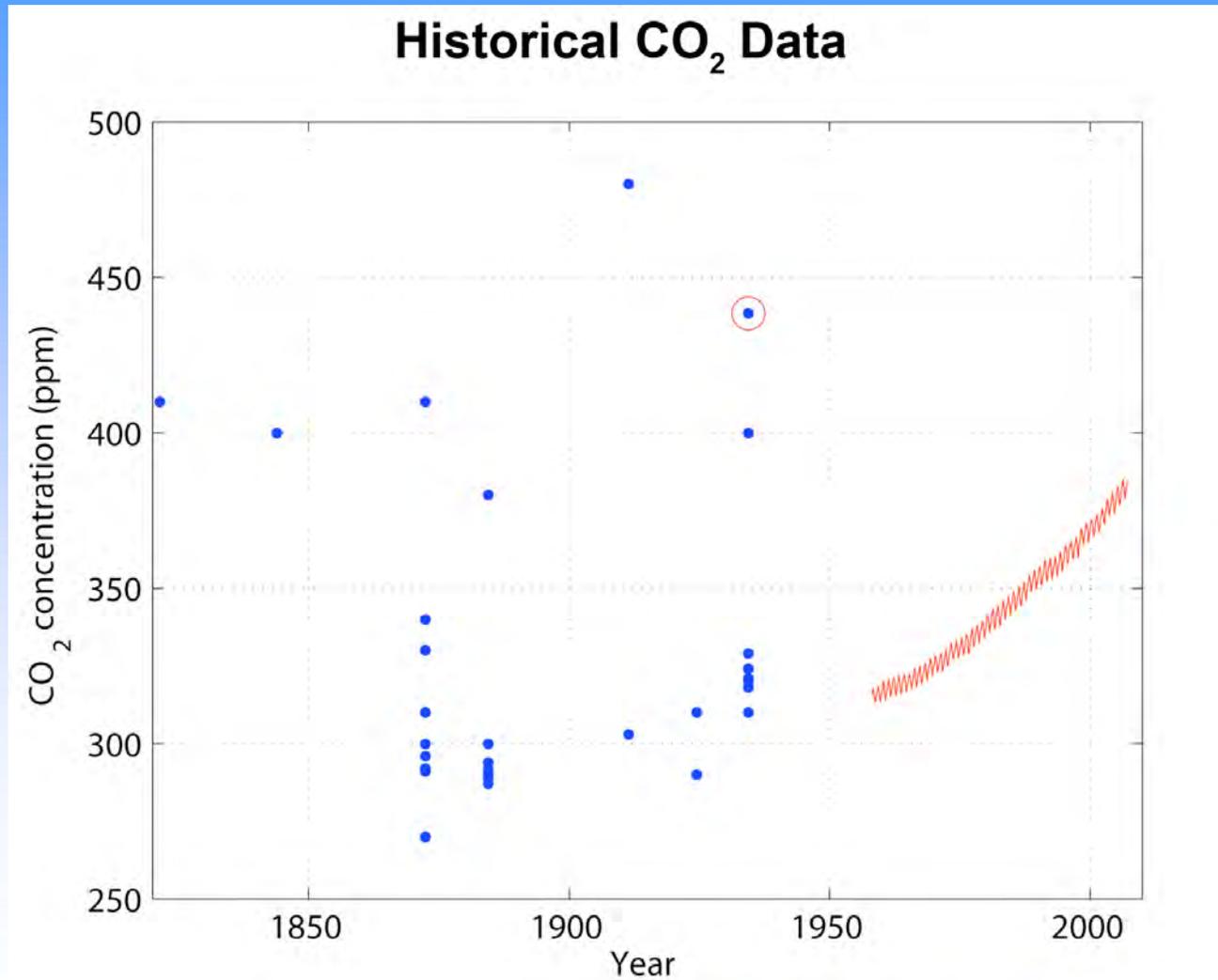
1. Completely independent methods of observing the most critical climate variables from space must be developed, each having accuracies that satisfy the requirements of climate (e.g., 0.1 K for temperature) and that are SI traceable on-orbit to absolute standards.
2. The fundamental requirements of climate must be recognized in the design of instruments that constitute the backbone of the national climate observation array: Optical Designs, Orbits, Calibration, etc.
3. Trust in the accuracy of key long-term climate observations must be built upon: (a) open access to the details of experimental execution; (b) publication in the scientific and technical literature; (c) individual scientific responsibility; and (d) continuity in laboratory, airborne, and satellite analyses that together dissect systematic errors.
4. The experimental design and execution of long-term climate observations must be cost effective, responsive to emerging knowledge, and adaptable to technological innovation.
5. Calibration and associated subsystem development resources must be given high priority and the analysis of accuracy achieved by the observing systems must be systematically critiqued over the period of decades. Fundamental development of calibration facilities at NIST must be supported with ongoing commitment.
6. Primary long-term climate observations must be global in coverage, must provide required accuracies in both horizontal and vertical structure, and must be free of interference from uncontrolled boundary conditions.
7. Climate forecast testing and improvement places specific demands upon the data vector produced by the climate observation and upon the mathematical structure used to couple the observations to the forecast. Thus, selection of the highest priority observations must be done in concert with an understanding of the structure of the forecast model.

# Achieving SI Traceability

The SI traceability requires two SI traceable standards : Pollock, D. B., T. L. Murdock, R. U. Datla, and A. Thompson, Data uncertainty traced to SI units. Results reported in the International System of Units, *International Journal of Remote Sensing*, 24(2), 225-235, 2003.

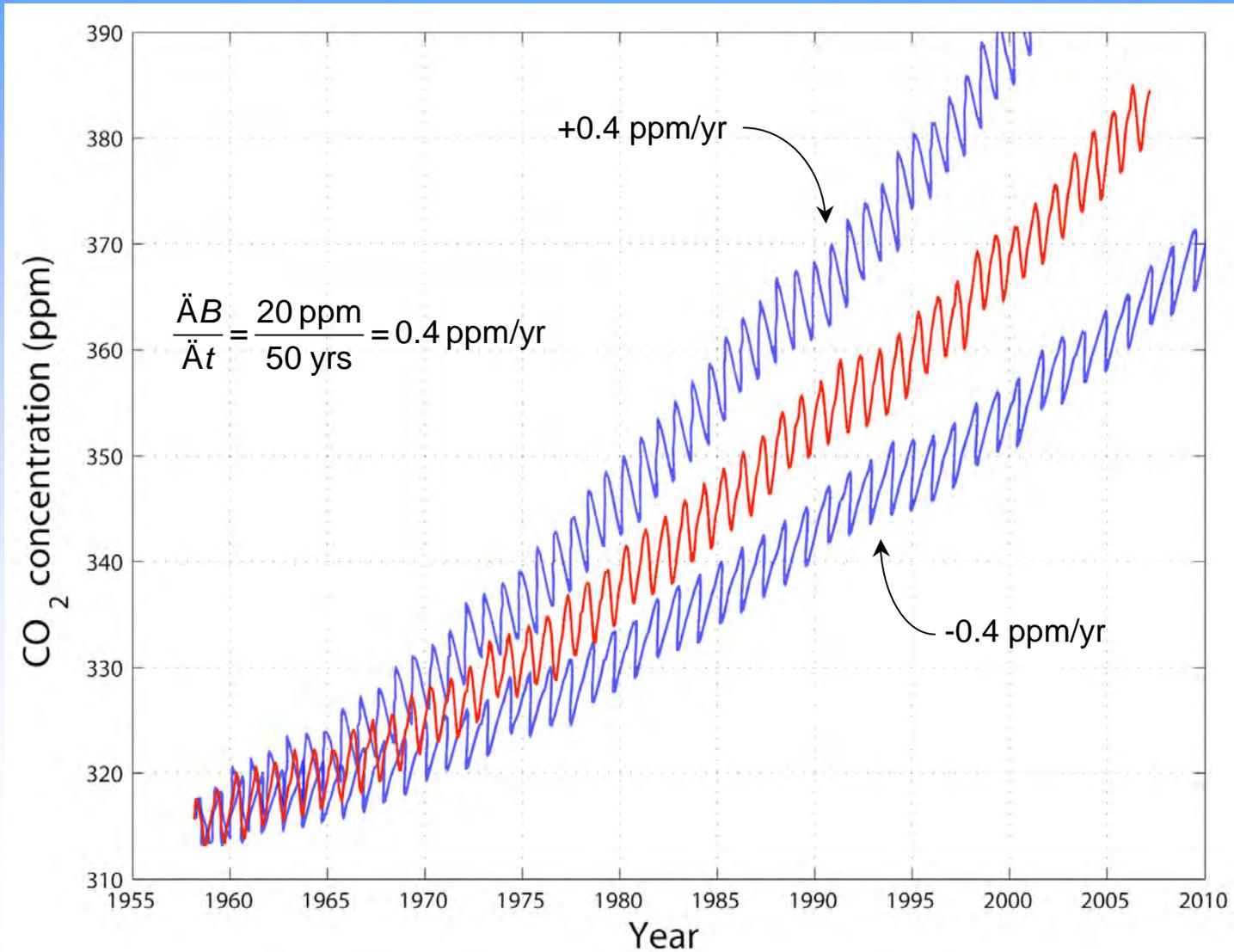


# Keeling Record: Historical CO<sub>2</sub>

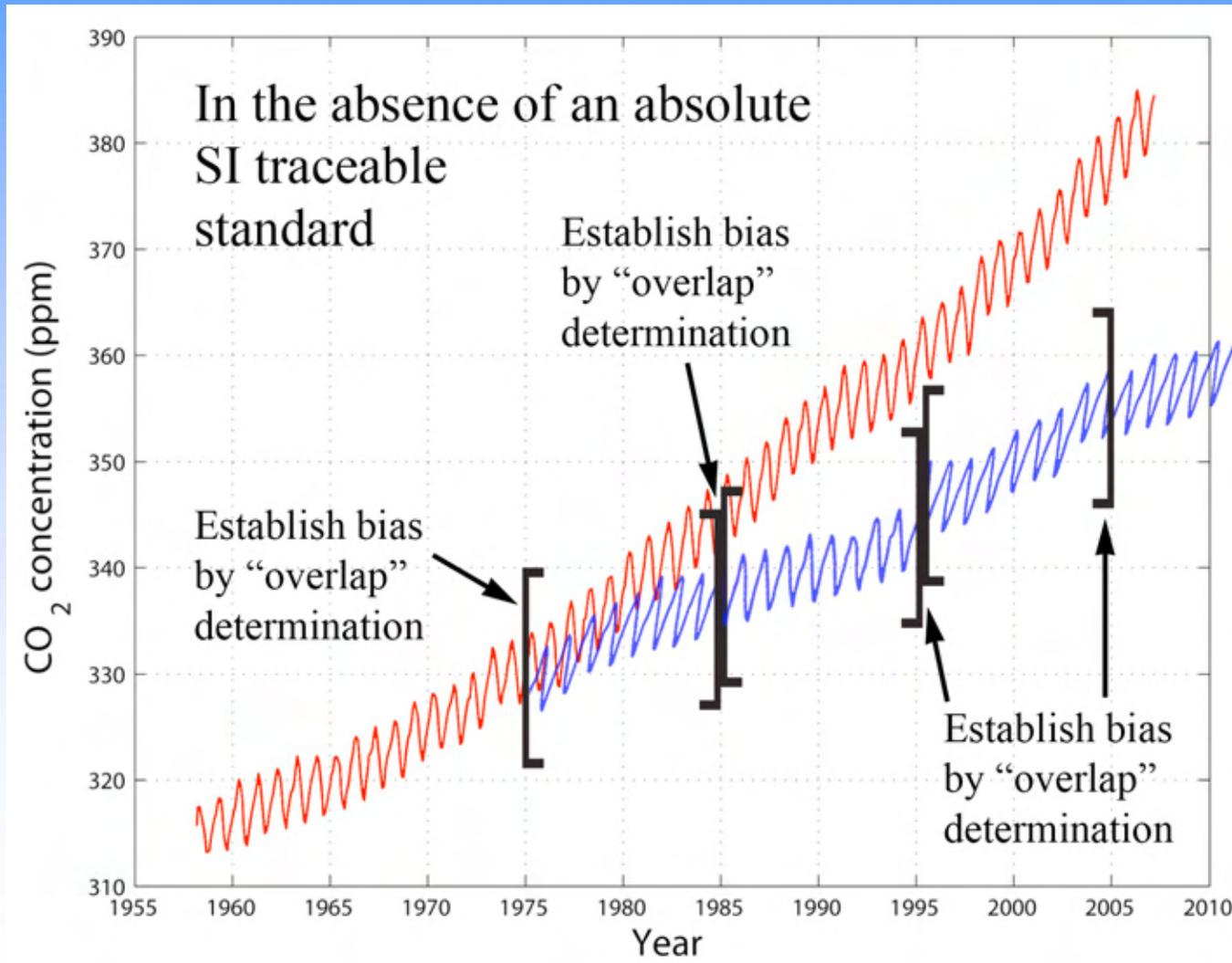


Slocum, 1955 - NOAA Global Monitoring Division

# Keeling Record with 3 Different $(\Delta B/\Delta t)/B$



# Assemble Keeling Record without SI Traceable Standard



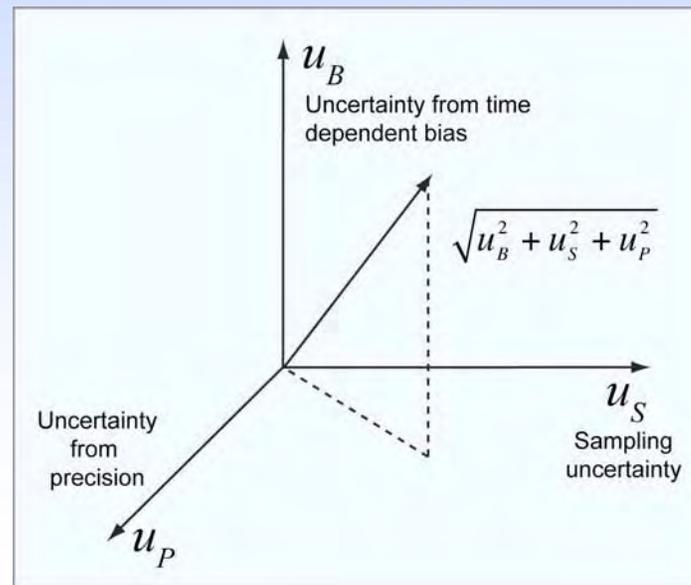
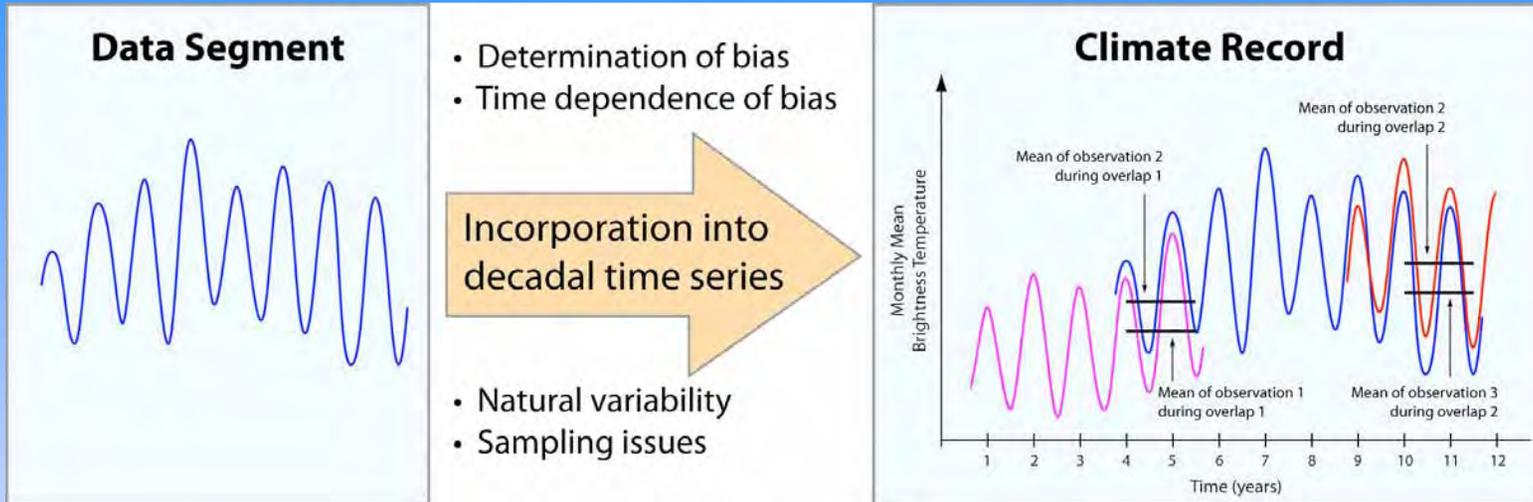
# Global Space-Based InterContinental System: GSICS

*For climate studies, accurate measurements of climate variables are vital for understanding climate processes and changes... However, it is not as necessary for monitoring long-term changes or trends as long as the data set has the required stability. And, when it comes to building satellite instruments, stability appears to be less difficult to achieve than accuracy.*

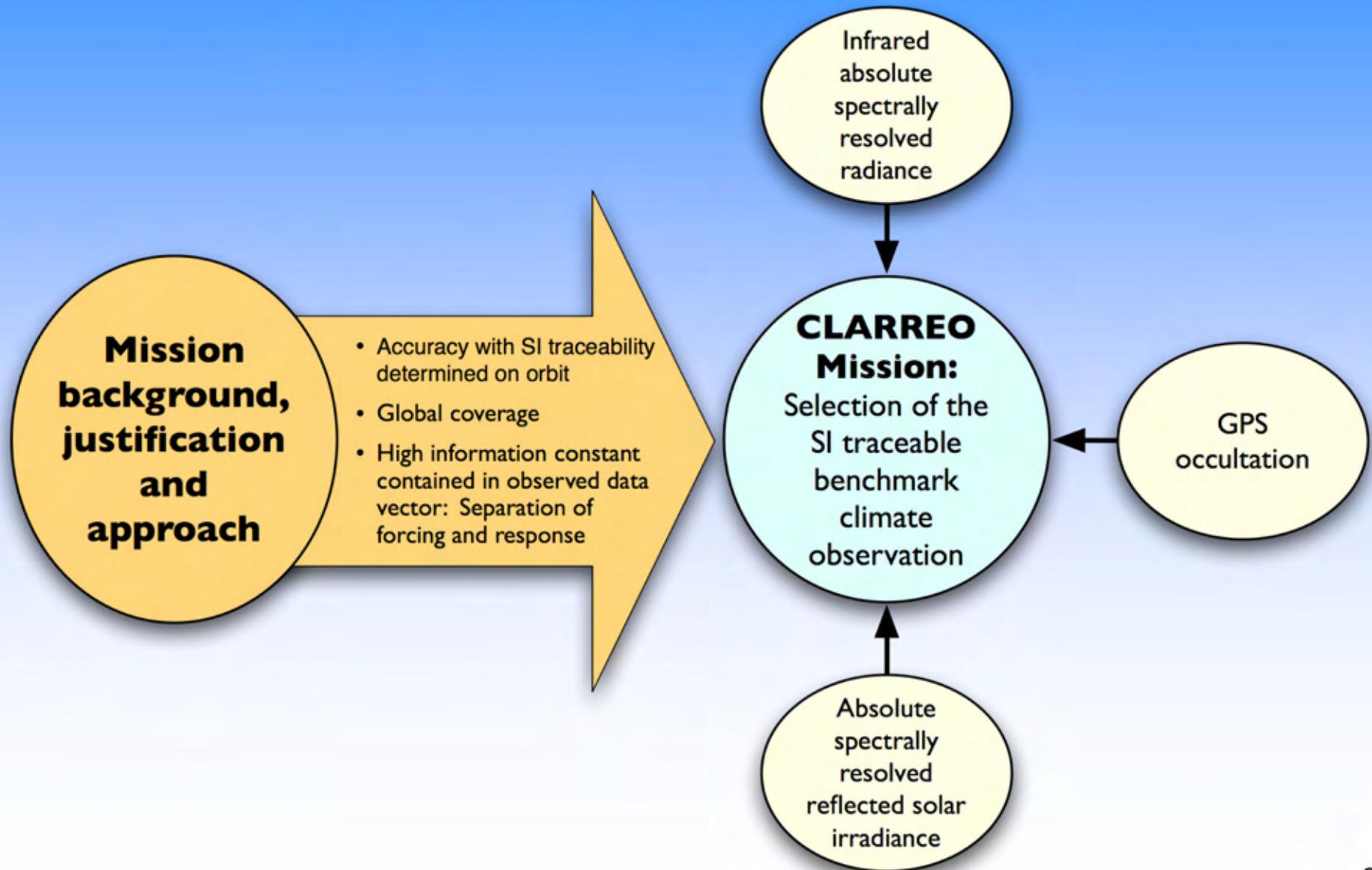
# Axiom

- ***Without*** an SI traceable (absolute) standard, time works ***against*** you.
- ***With*** an SI traceable (absolute) scale, time works ***for*** you.

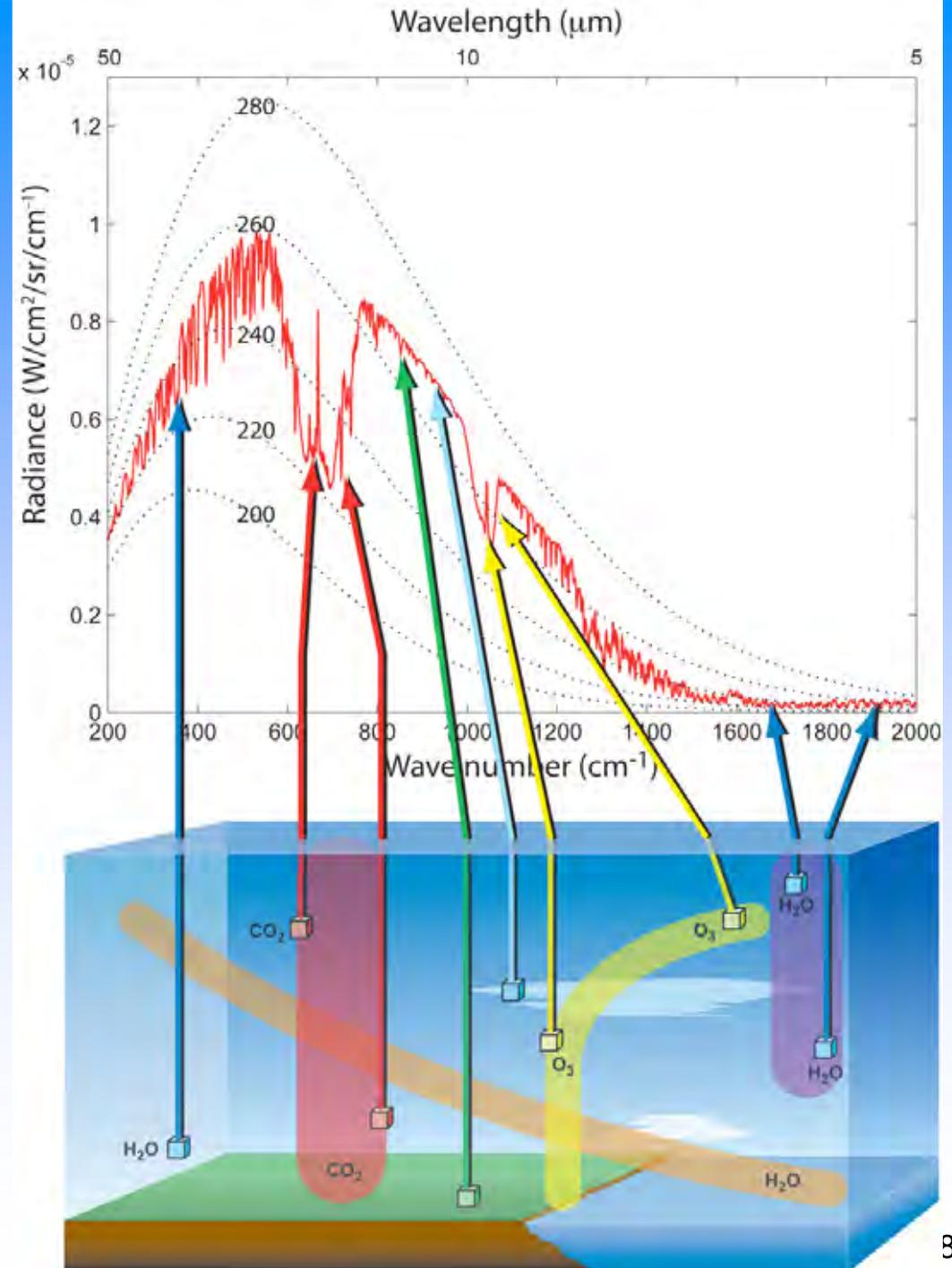
# Inclusion of Data Segment



# Establishing the Climate Benchmark Record: What are the Requirements?

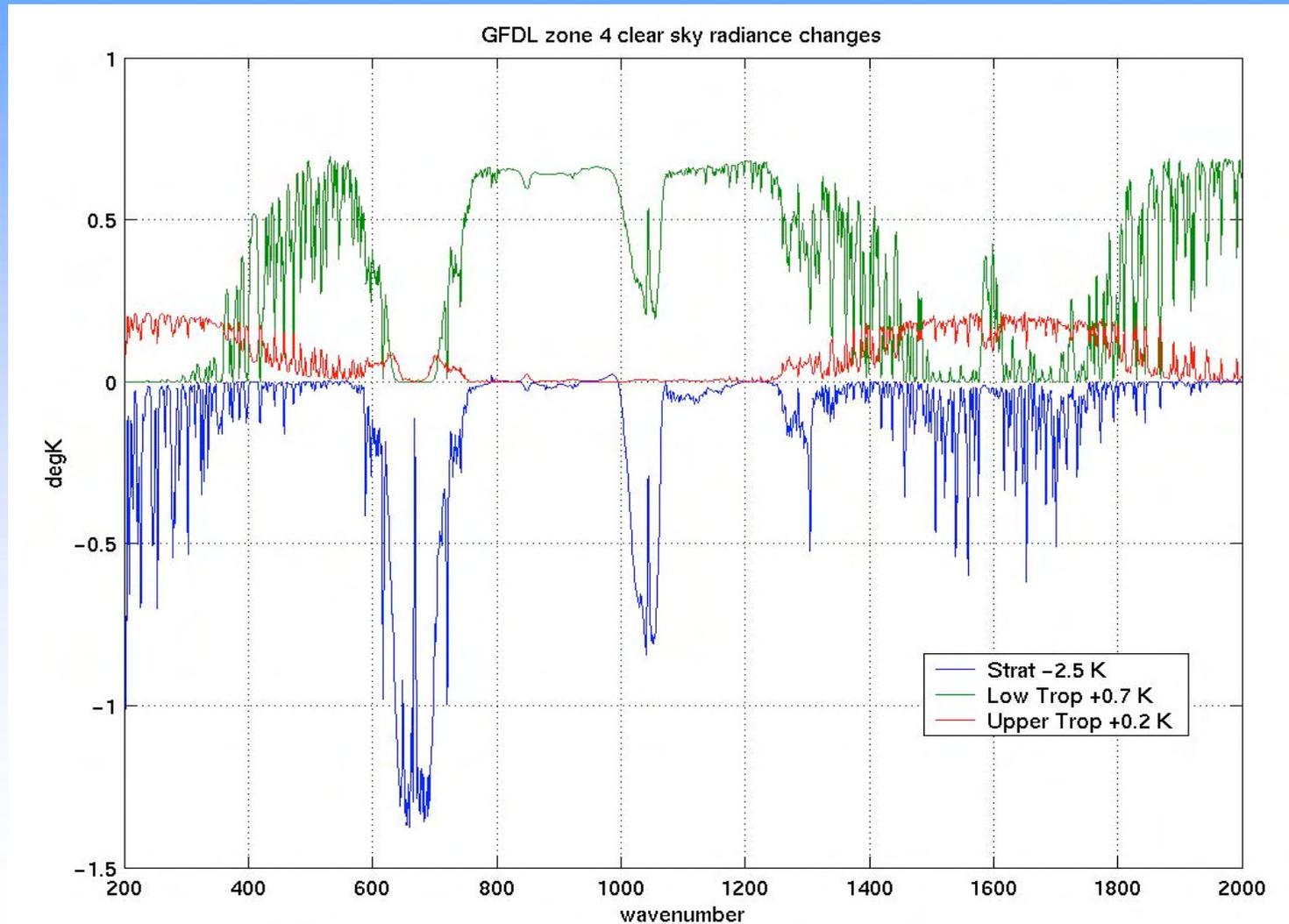


Importance of IR:  
Why did NRC  
emphasize for the  
climate record?

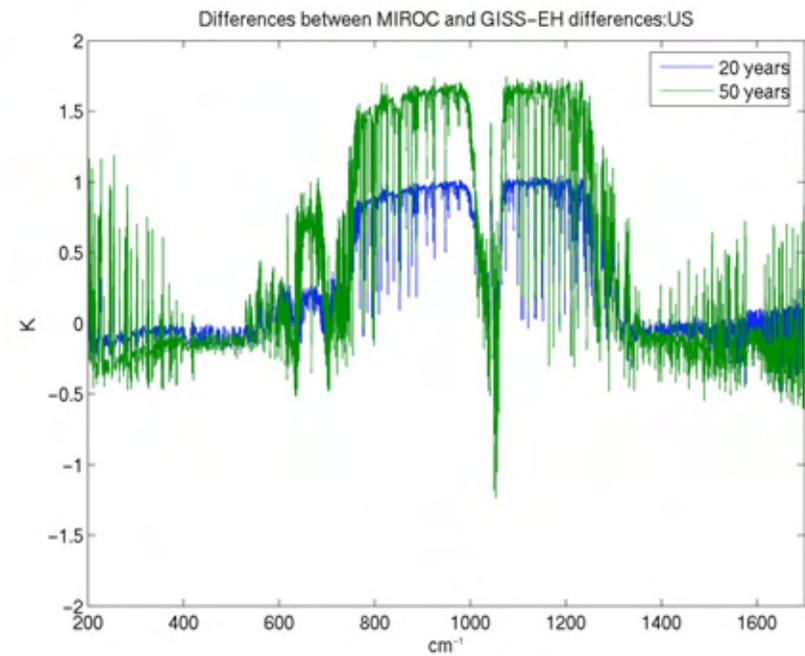
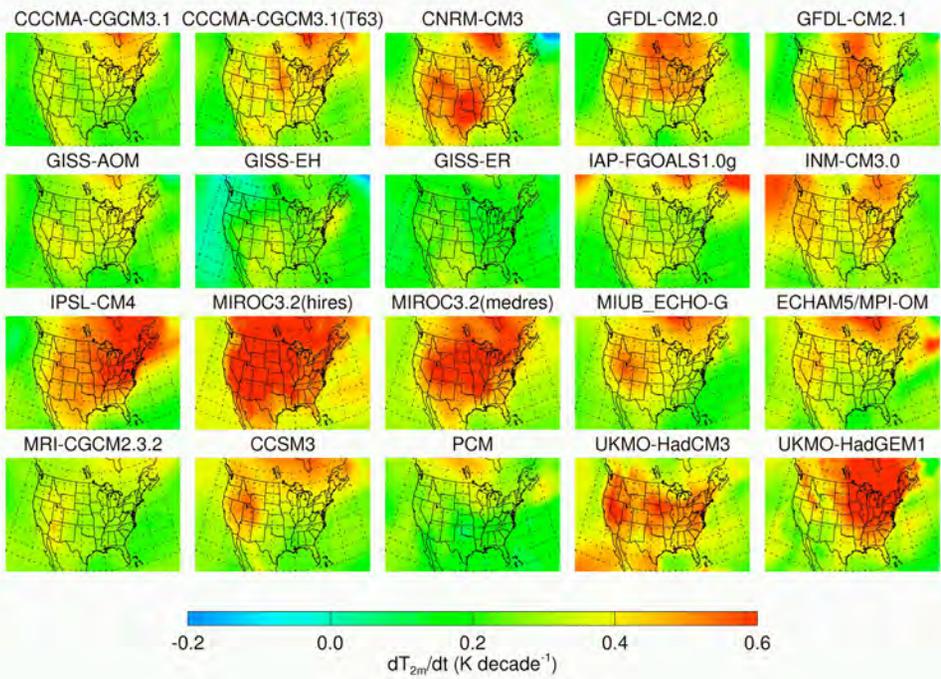


# Importance of IR: Difference Spectra

GFDL Zonal Average centered around 11°S Clear Sky Radiance Changes



# Radiance Differences for Selected 4AT Model at Midlatitude



# Testing Climate Models

Response = Forcing × Sensitivity


$$\Delta T = \Delta F_{\text{rad}} \times \left( \Gamma - \sum_i \gamma_i^{\text{LW}} - \sum_i \gamma_i^{\text{SW}} \right)^{-1}$$

Longwave feedbacks  $\Rightarrow \gamma_i^{\text{LW}} = \left( \frac{\partial F^{\text{LW}}}{\partial x_i} \right) \frac{dx_i}{dT}$

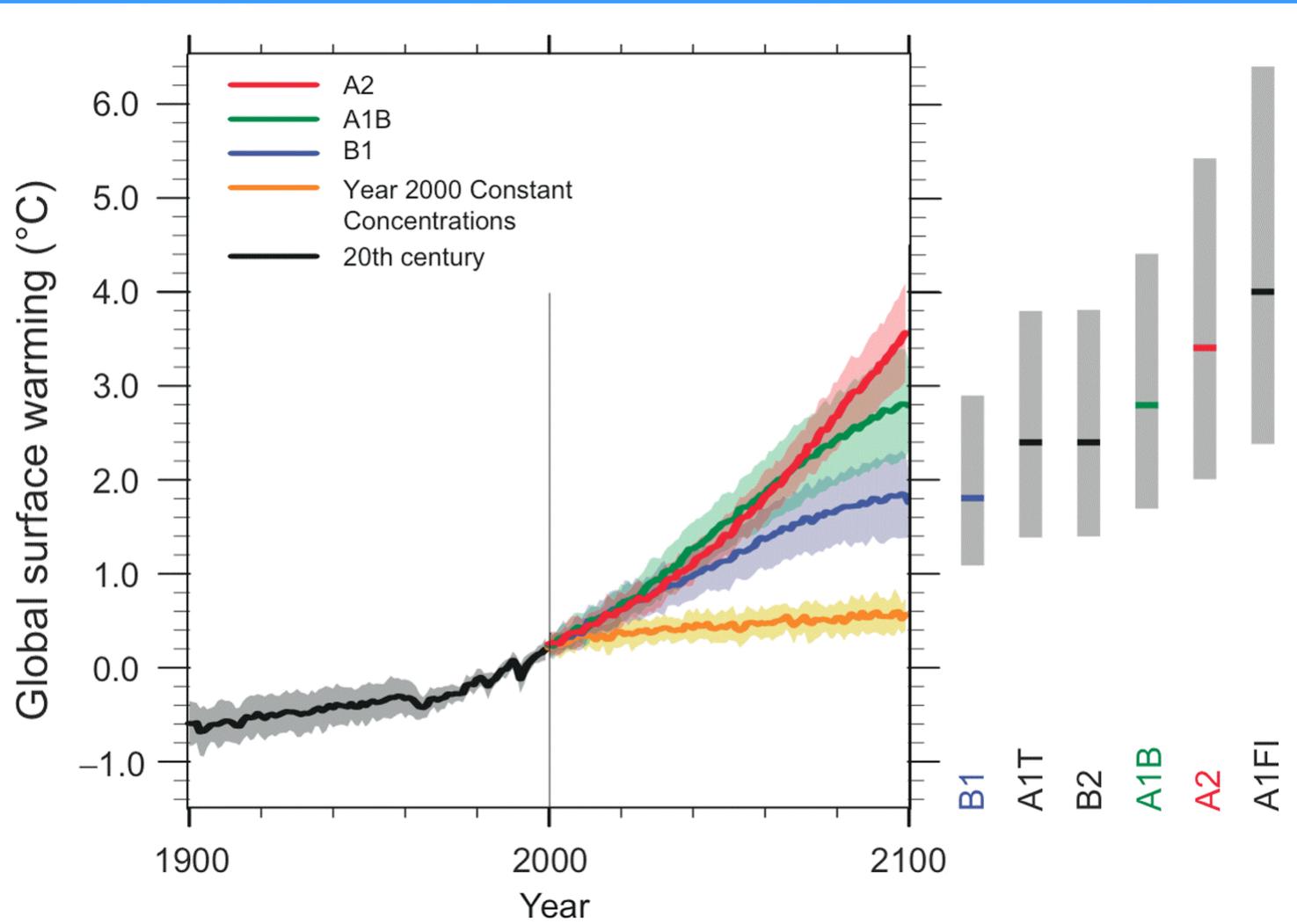
Shortwave feedbacks  $\Rightarrow \gamma_i^{\text{SW}} = \left( \frac{\partial F^{\text{SW}}}{\partial x_i} \right) \frac{dx_i}{dT}$

# **Decadal Survey CLARREO Mission**

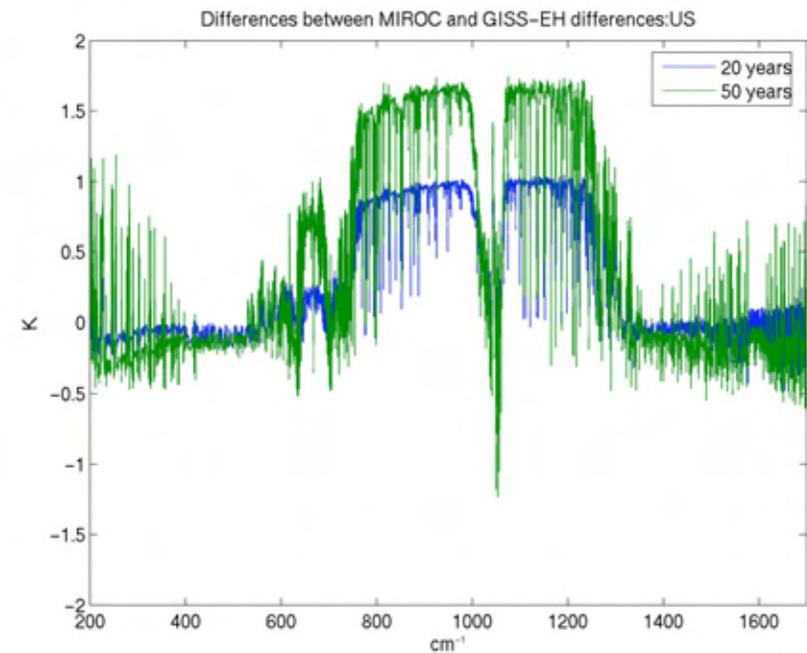
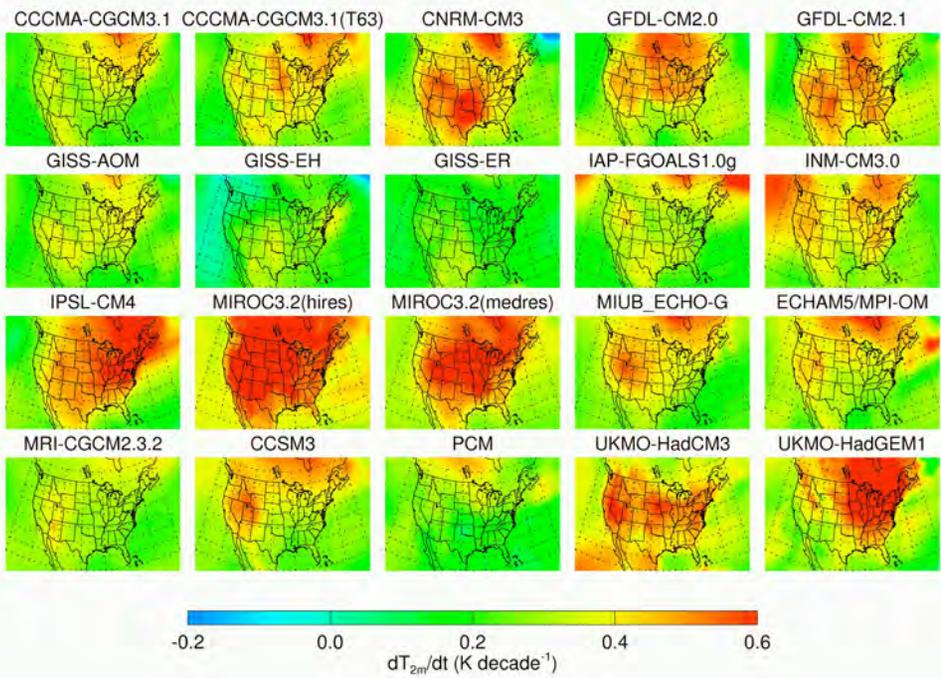
**NRC Decadal Survey Objective: Testing  
Climate Forecast Models**

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# Radiance Differences for Selected 4AT Model at Midlatitude



# Testing Climate Models

Response = Forcing × Sensitivity

$$\Delta T = \Delta F_{\text{rad}} \times \left( \Gamma - \sum_i \gamma_i^{\text{LW}} - \sum_i \gamma_i^{\text{SW}} \right)^{-1}$$

$$\Gamma = \Delta F_{\text{RAD}} / \Delta T$$

Planck response to radiative forcing  $\Delta F_{\text{RAD}}$

Stefan-Boltzmann

$$F = \epsilon \sigma T^4$$

$$\Delta F_{\text{RAD}} / \Delta T = 4\epsilon \sigma T^3 = \Gamma$$

$$\gamma_1 = 1.7 \text{ w/m}^2\text{-K} \quad (\text{water vapor})$$

$$\gamma_2 = -0.3 \text{ w/m}^2\text{-K} \quad (\text{lapse rate})$$

$$\gamma_3 = 0.5 \text{ w/m}^2\text{-K} \quad (\text{clouds})$$

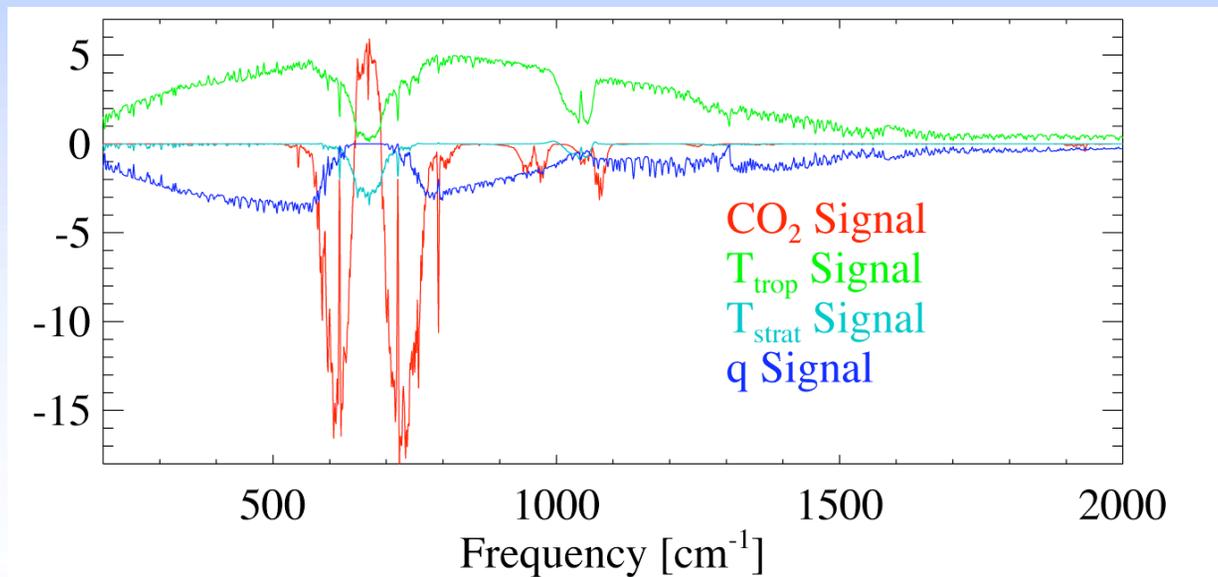
$$\gamma_4 = 0.5 \text{ w/m}^2\text{-K} \quad (\text{surface albedo in cryosphere})$$

$$\gamma_i = \left( \frac{\partial F}{\partial x_i} \right) \left( \frac{dx_i}{dT} \right)$$

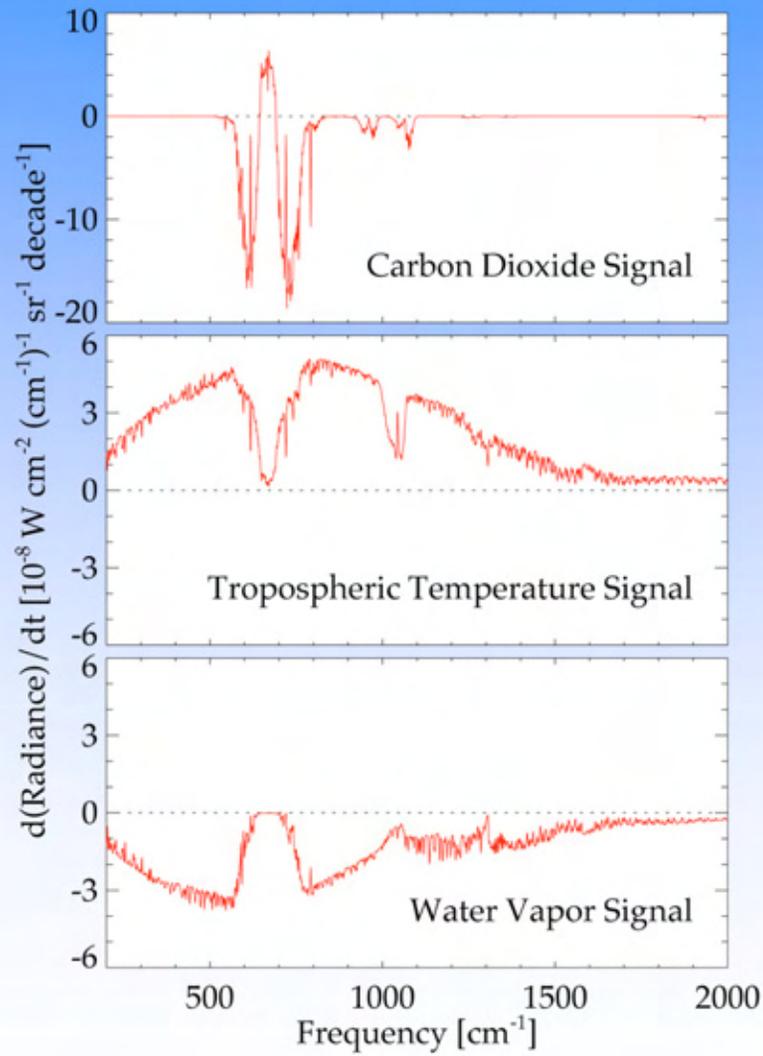
# Deconstructing the IR Signal

$$T(\mathbf{r}, p, m, t) = T_0(\mathbf{r}, p, m) + t \frac{dT}{dt}(\mathbf{r}, p, m) + dT(\mathbf{r}, p, m, t)$$

$$\ln q(\mathbf{r}, p, m, t) = \ln q_0(\mathbf{r}, p, m) + t \frac{d \ln q}{dt}(\mathbf{r}, p, m) + d \ln q(\mathbf{r}, p, m, t)$$



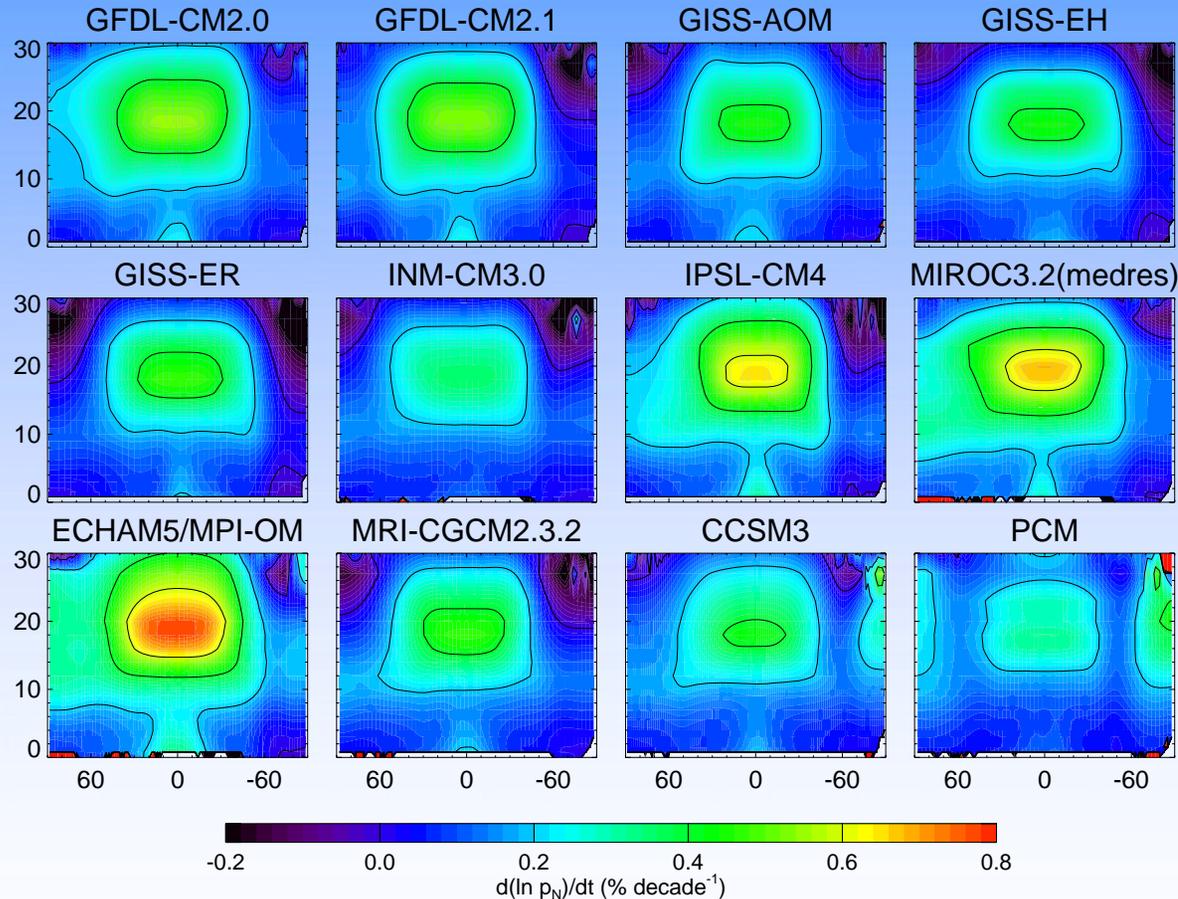
# Information in Infrared



Obtain part of feedbacks

$$\gamma_i = \left( \frac{\partial F}{\partial x_i} \right) \frac{dx_i}{dt} \times \left( \frac{dT}{dt} \right)^{-1}$$

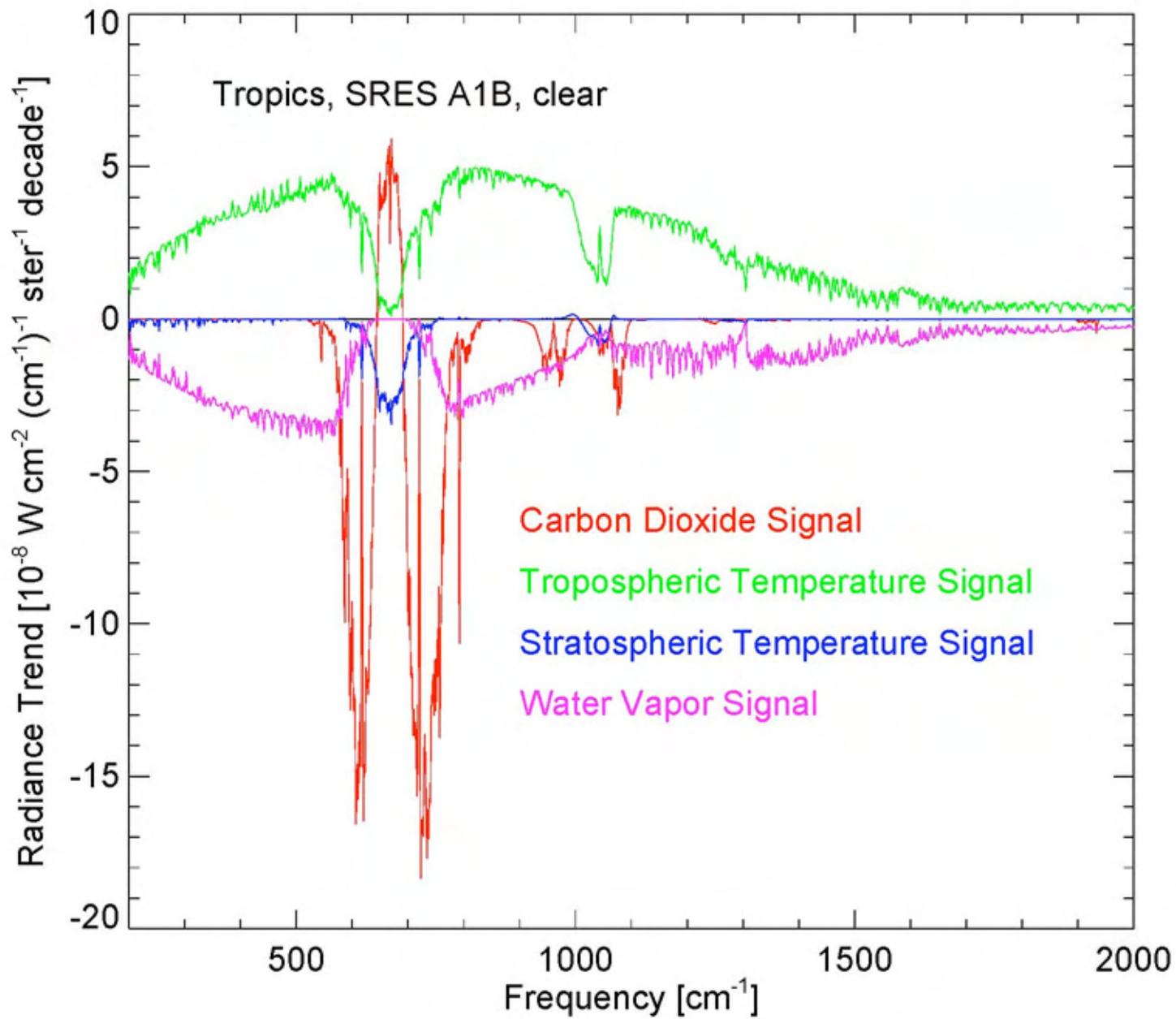
# Information in GPS Occultation



Obtain climate “response” by observing jet stream migration, widening of Hadley cell, expansion of troposphere.

Obtain response to 10% uncertainty in 29 years (SRES-A1B).

$$\gamma_i = \left( \frac{\partial F}{\partial x_i} \right) \frac{dx_i}{dt} \times \left( \frac{dT}{dt} \right)^{-1}$$



# Optimal Fingerprinting

Find signal amplitudes ( $\alpha_m$ ) and uncertainty ( $\Sigma_\alpha$ ) in a data set ( $\mathbf{d}$ ) according to the signals' patterns ( $\mathbf{s}_j$ ) against a background of natural variability, the eigenvectors and eigenvalues of which are  $\mathbf{e}_\mu$  and  $\lambda_\mu$ .

$$\alpha_m = \mathbf{G}^{-1} \mathbf{h}$$

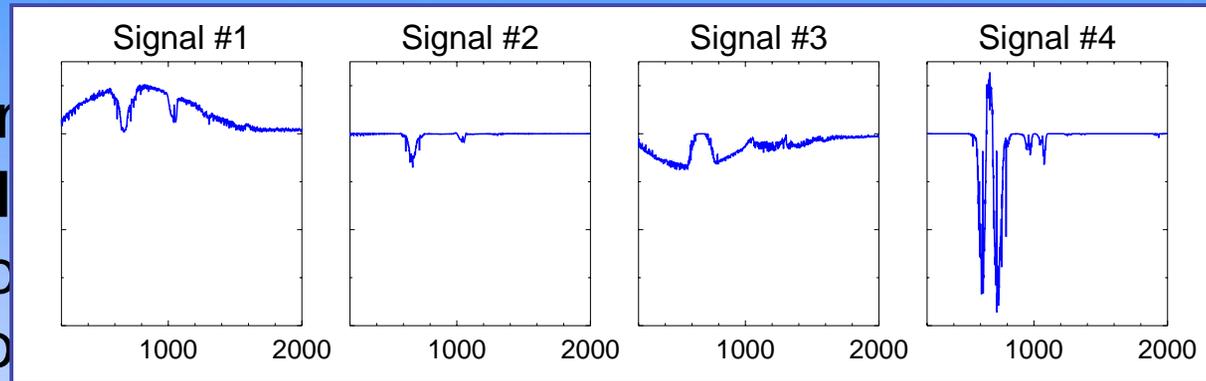
$$\Sigma_\alpha = \mathbf{G}^{-1}$$

$$h_i = \sum_{\mu=1}^k \lambda_\mu^{-1} \langle \mathbf{e}_\mu, \mathbf{s}_i \rangle \langle \mathbf{e}_\mu, \mathbf{d} \rangle$$

$$G_{i,j} = \sum_{\mu=1}^k \lambda_\mu^{-1} \langle \mathbf{e}_\mu, \mathbf{s}_i \rangle \langle \mathbf{e}_\mu, \mathbf{s}_j \rangle$$

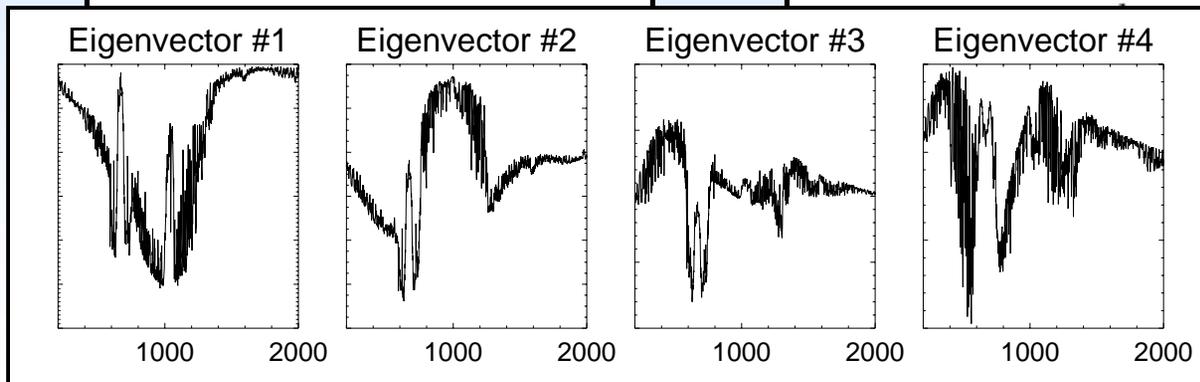
# Optimal Fingerprinting

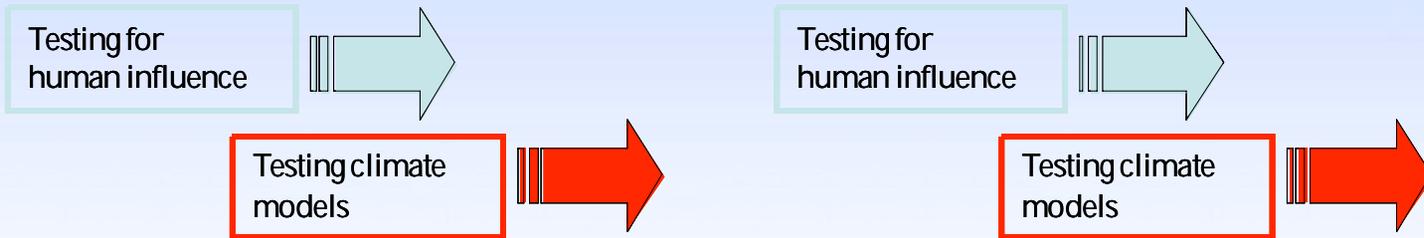
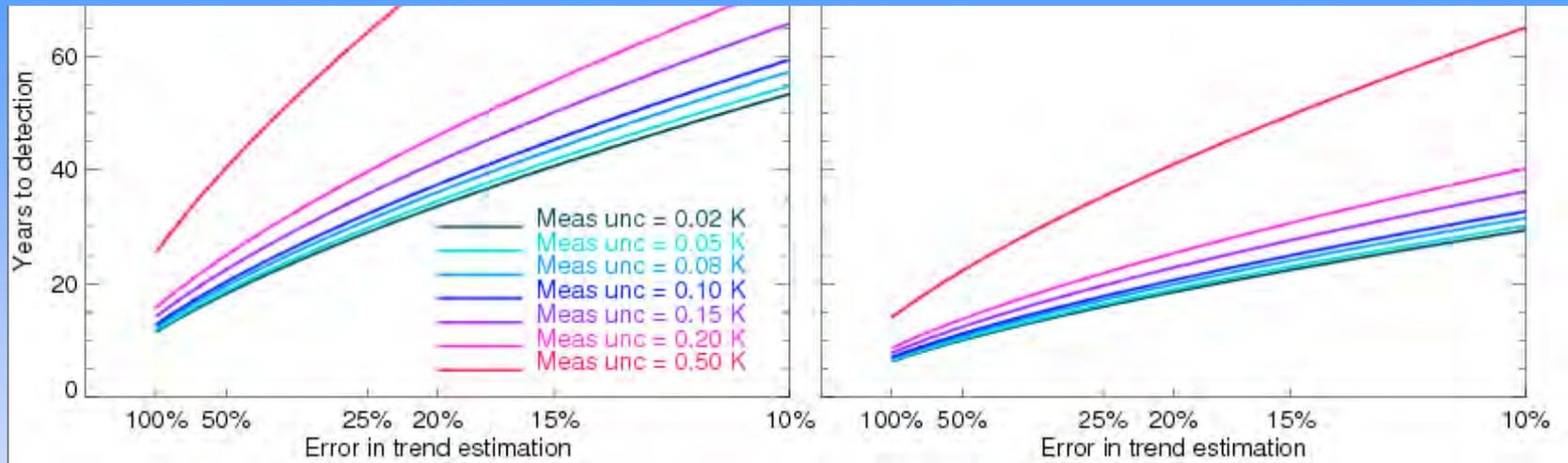
Find signal and data set ( $\mathbf{d}$ ) against a basis of eigenvectors



$$\alpha_m = \mathbf{G}^{-1} \mathbf{h}$$

$$h_i = \sum_{\mu=1}^k \lambda_{\mu}^{-1} \langle \mathbf{e}_{\mu}, \mathbf{s}_i \rangle \langle \mathbf{e}_{\mu}, \mathbf{d} \rangle$$





# Conclusions

- Absolute Spectrally Resolved Radiance (ASRR) in the IR in Combination with GPS Constitute a Powerful Observational Foundation for far more Stringent Tests of Climate Forecast Models
- The Systematic Testing and Improvement of Decadal Climate Forecast Models is Mathematically Linked to the Data Vectors Provided by ASRR and GPS such that Both Trends and the Gain Terms in Climate Feedback can be Observed.
- Optimal Fingerprinting Provides both the Optimization of Time-to-Detect and a Quantitative Measure of the S/N Ratio of that Determination

# **Decadal Survey CLARREO Mission**

## **Instrument Design to Meet NRC Variability Requirement**

CLARREO Workshop

17-19 July 2007

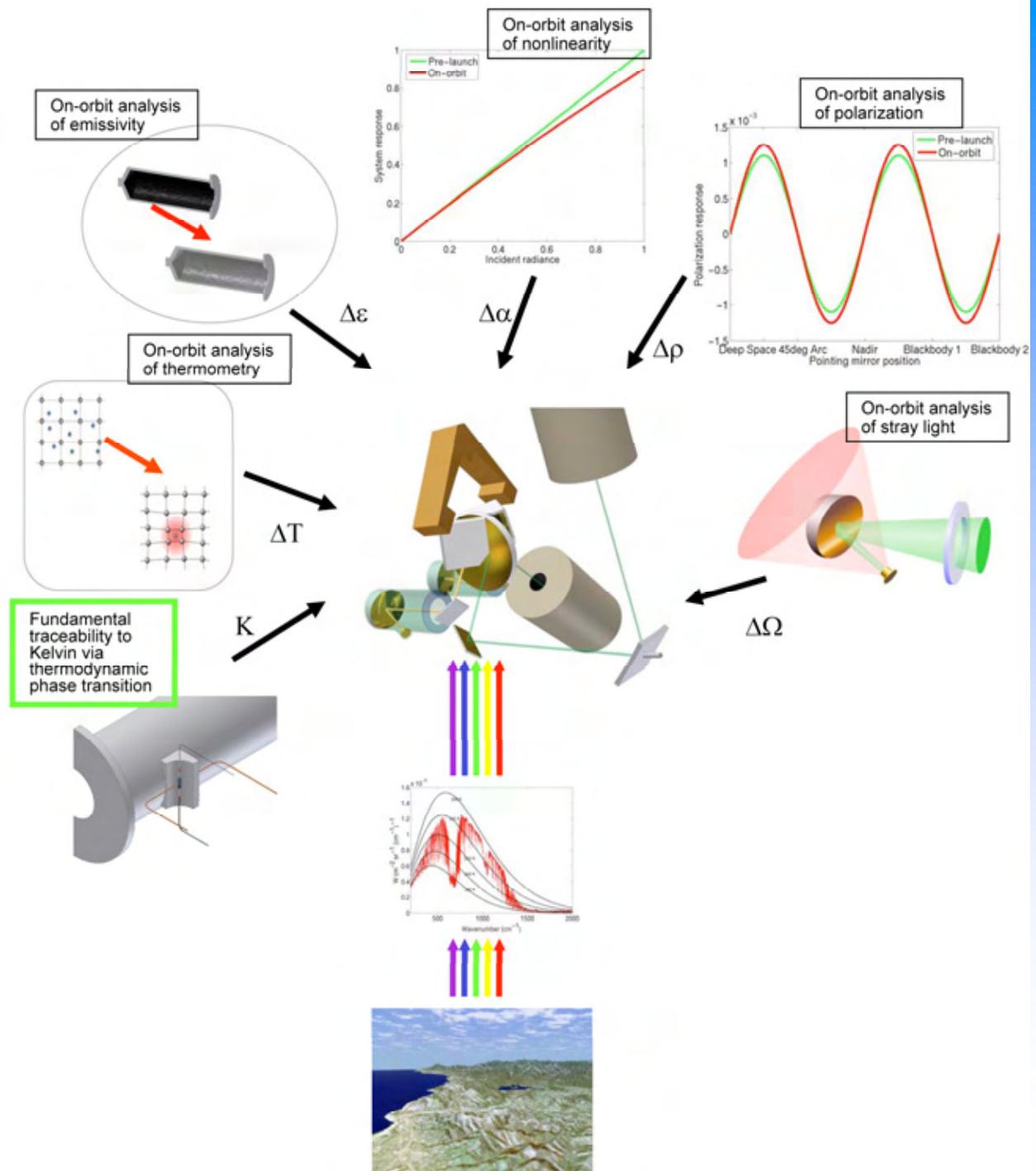
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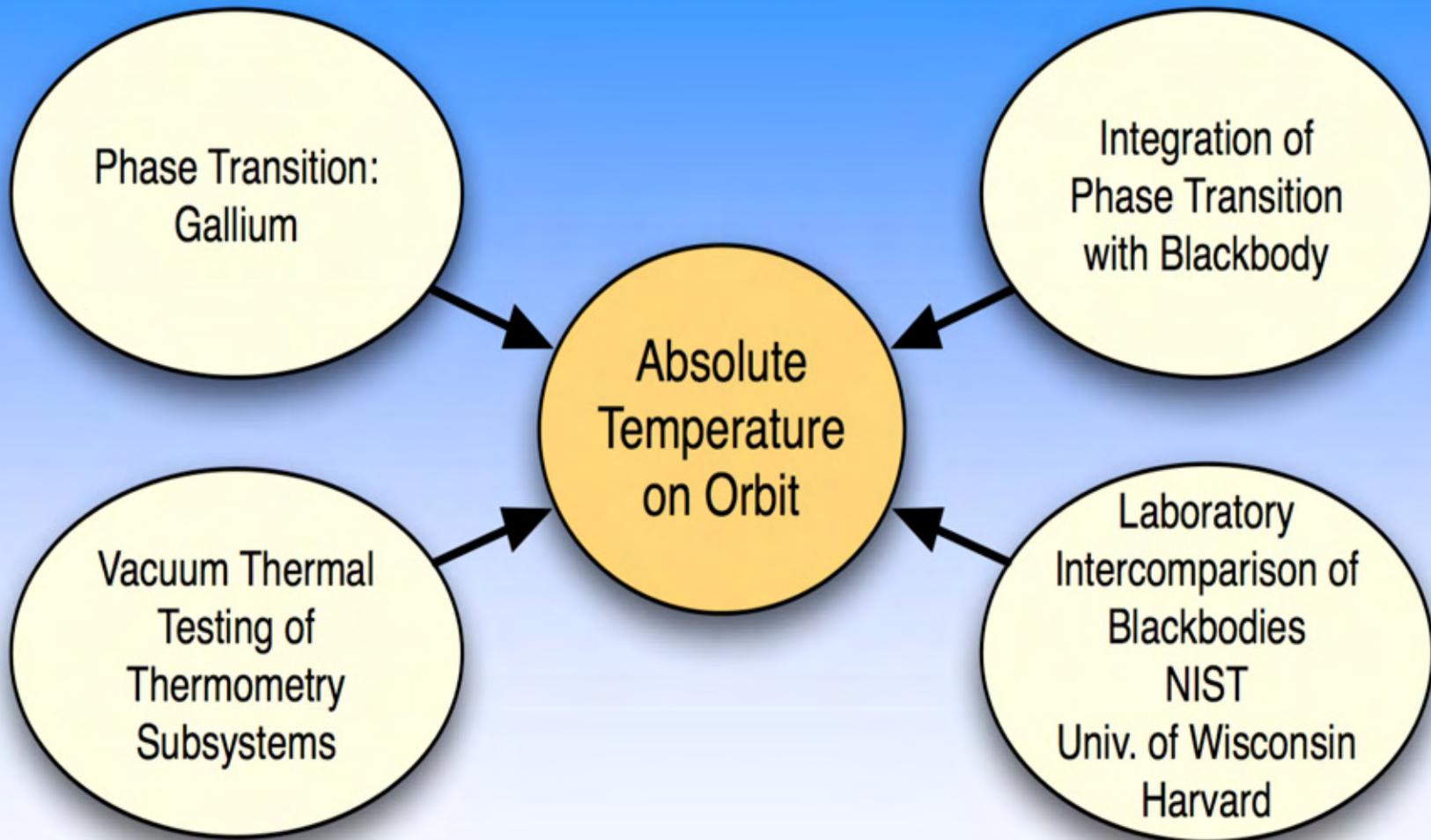
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# Uncertainty (Error) Budget for Infrared

| <b>Subsystem</b>                    | <b>Magnitude<br/>(mK)</b> |
|-------------------------------------|---------------------------|
| Thermometry                         | 10                        |
| Blackbodies                         |                           |
| Homogeneity                         | 20                        |
| Emissivity                          | 9                         |
| FTS stray light and<br>polarization | 33                        |
| Detector chain<br>nonlinearity      | 14                        |
| Other errors                        | 10                        |
| <b>TOTAL</b>                        | <b>44</b>                 |

# Constellation of Error Analysis Contributions



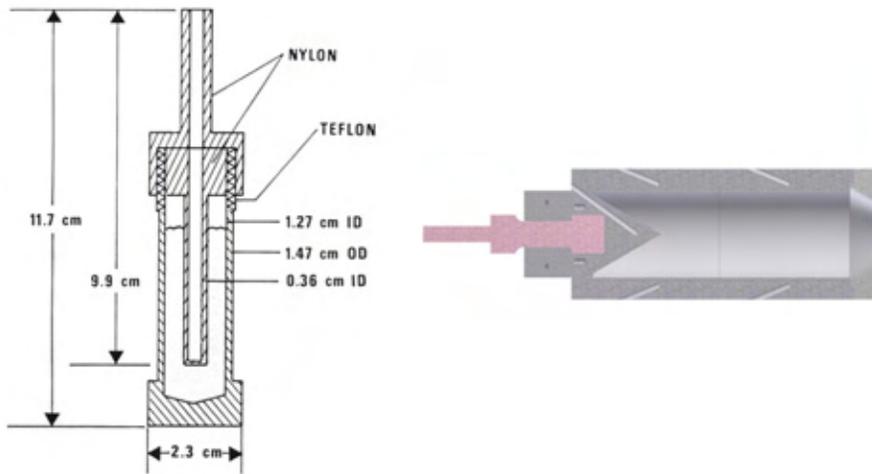


# SI Temperature On-Orbit: Phase Transition/Gallium

Phase Transition:  
Gallium

Absolute  
Temperature  
on Orbit

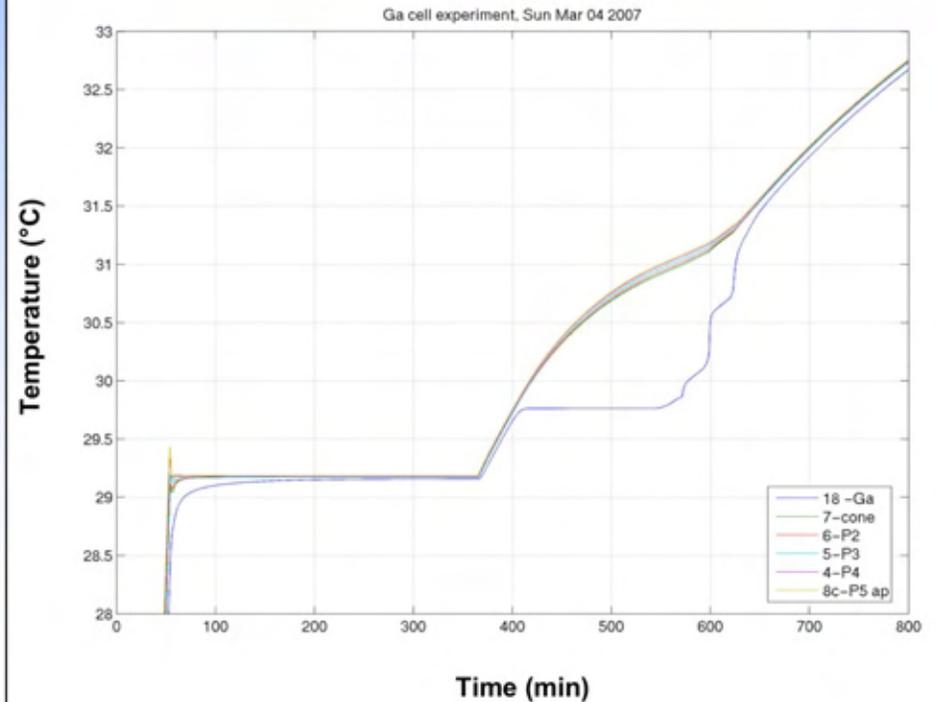
## Gallium-cell Blackbody Mechanical Design



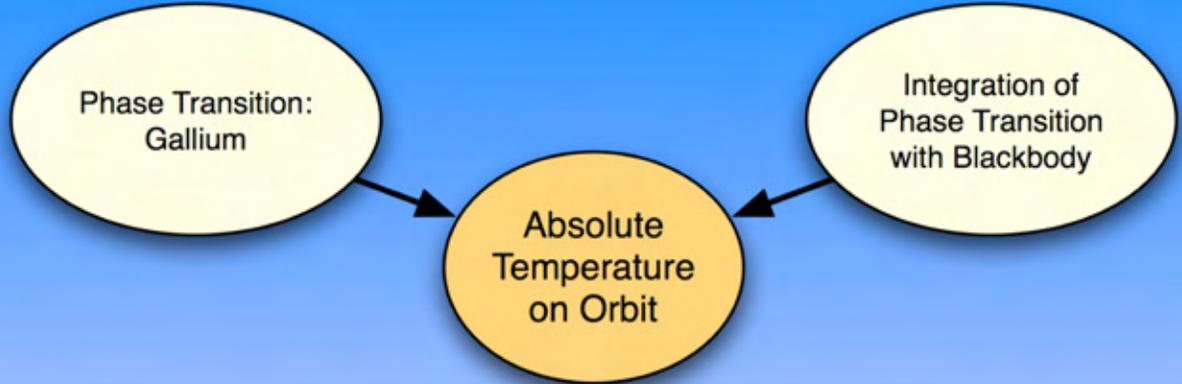
NIST SRM 1968  
Gallium melting point  
standard

Blackbody with  
embedded fixed  
point cell

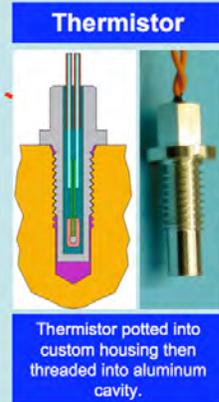
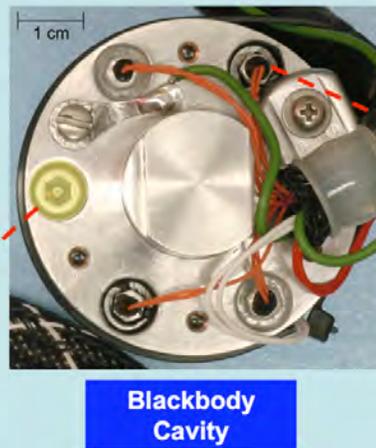
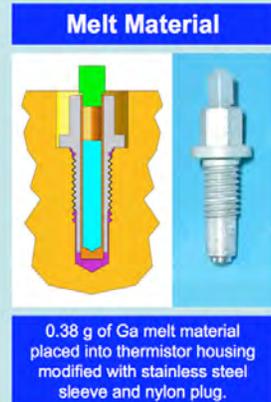
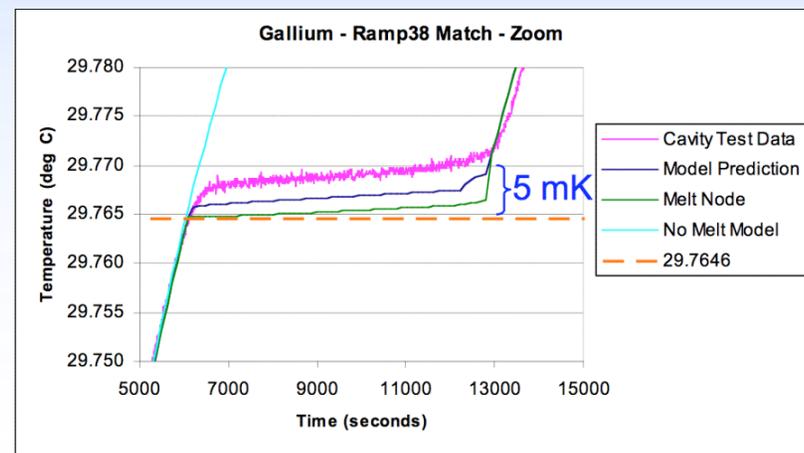
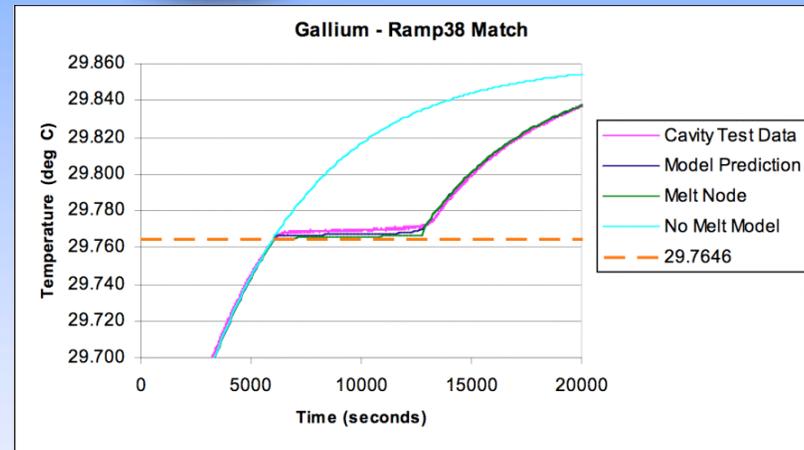
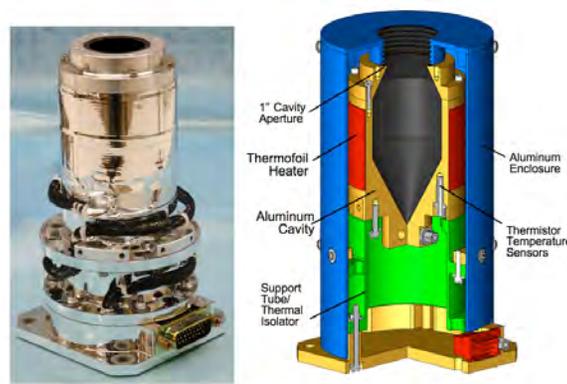
## Phase Transition Temperature Plateau



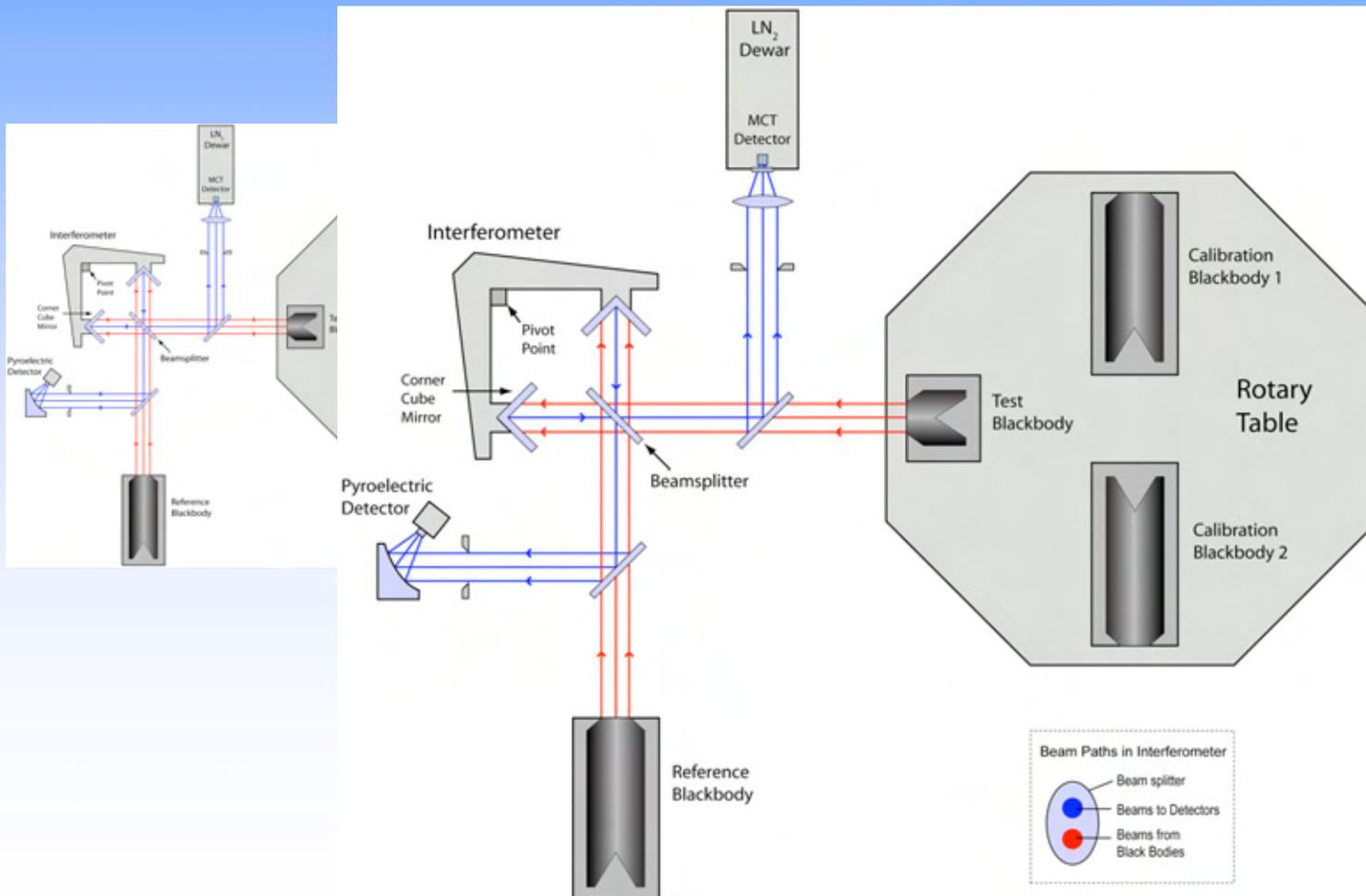
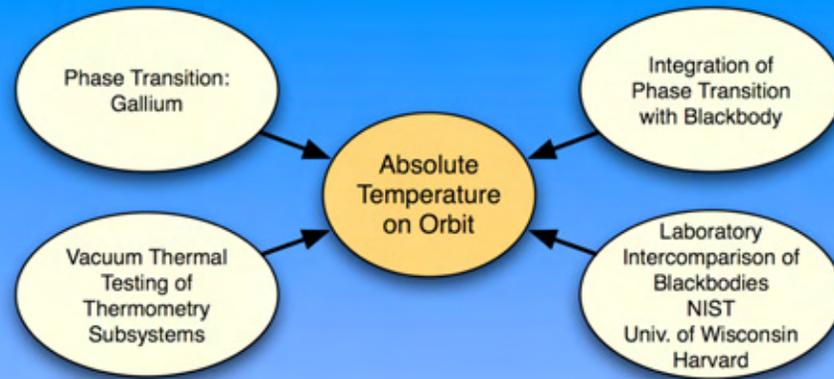
# SI Temperature On-Orbit: Integration of Phase Transition Cell with Blackbody



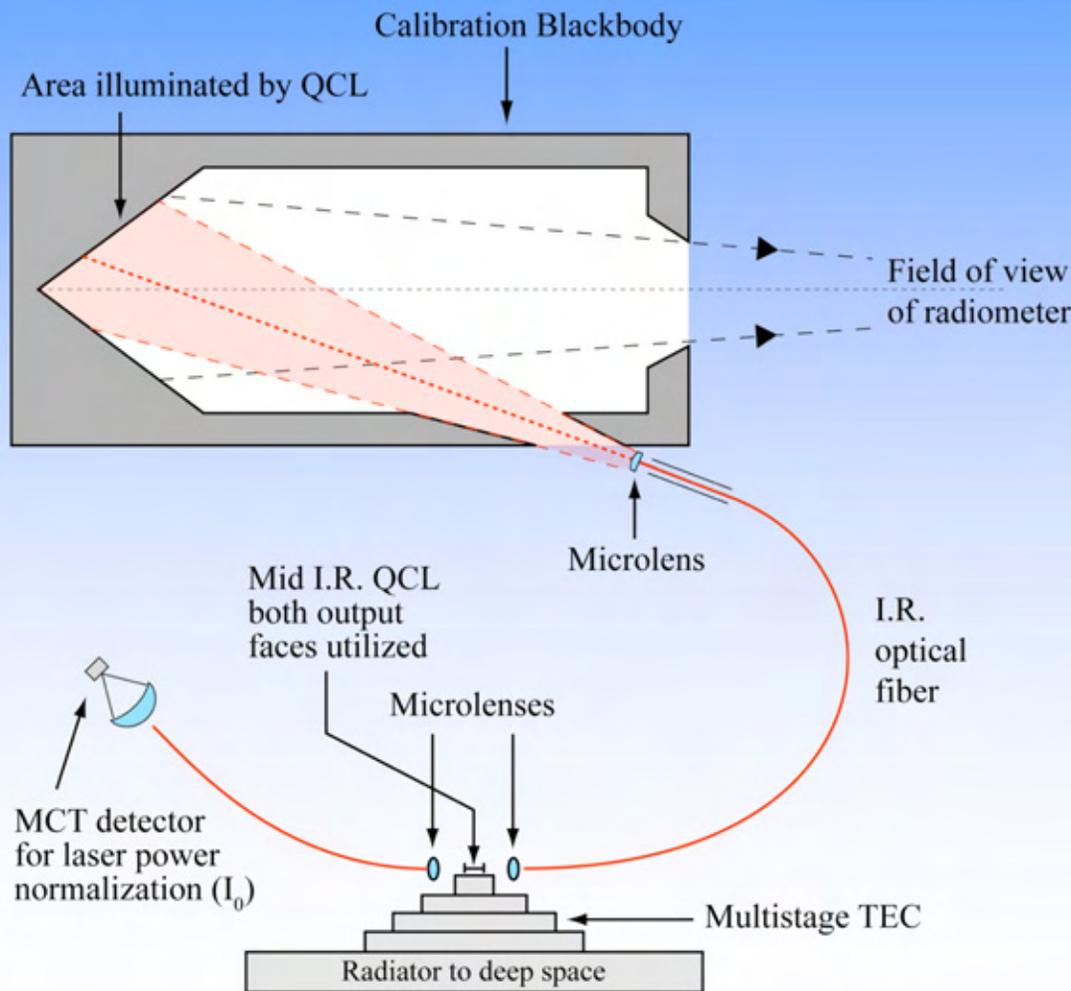
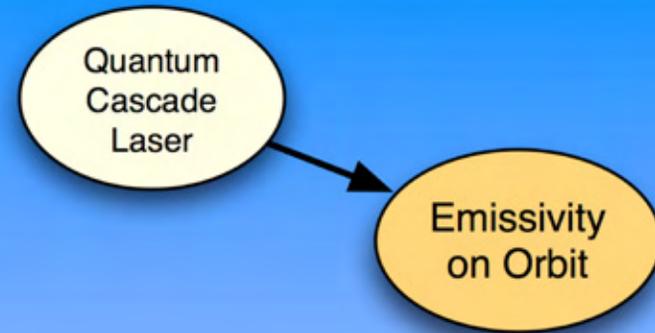
| Key Parameter             | Specification         | As Delivered |
|---------------------------|-----------------------|--------------|
| Measurement Range         | 233 to 313 K          | 233 to 313 K |
| Temperature Uncertainty   | < 0.1 K (3 $\sigma$ ) | < 0.056 K    |
| Blackbody Emissivity      | > 0.996               | > 0.999      |
| Emissivity Uncertainty    | < 0.002 (3 $\sigma$ ) | < 0.00072    |
| Entrance Aperture         | 1.0 inch              | 1.0 inch     |
| Mass (2 BBs + controller) | < 2.4 kg              | 2.1 kg       |
| Power (average/max)       | < 2.2/5.2 W           | 2.2/5.2 W    |



# Laboratory Intercomparison of Blackbodies

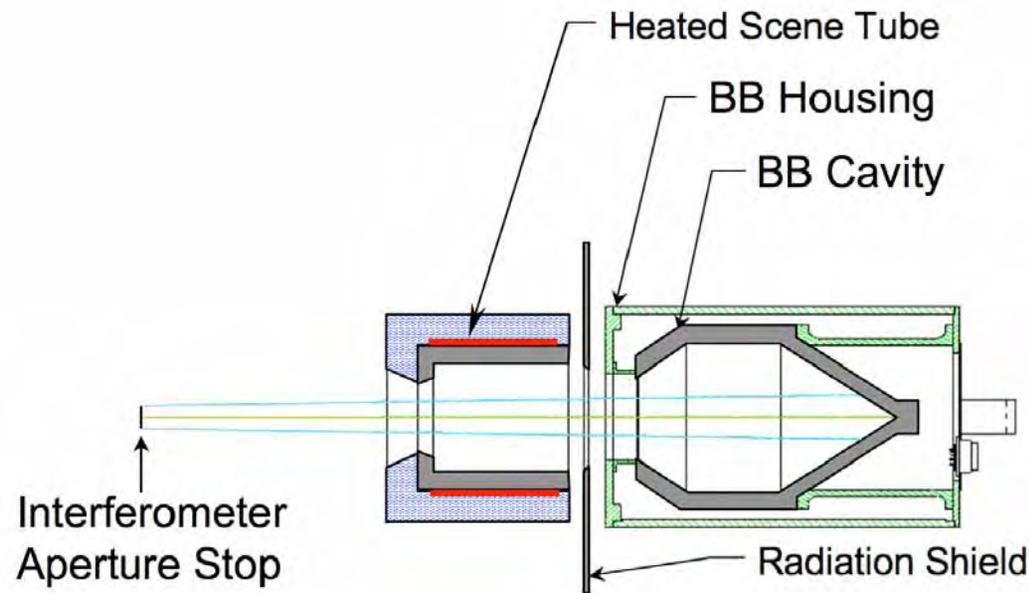
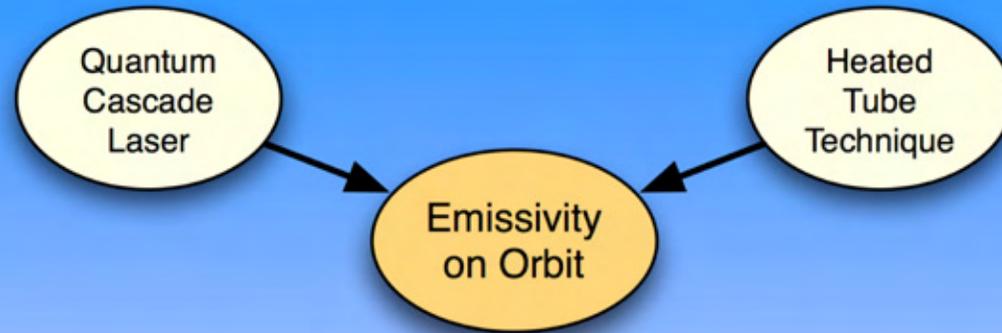


# Determination of Emissivity On Orbit: Quantum Cascade Laser



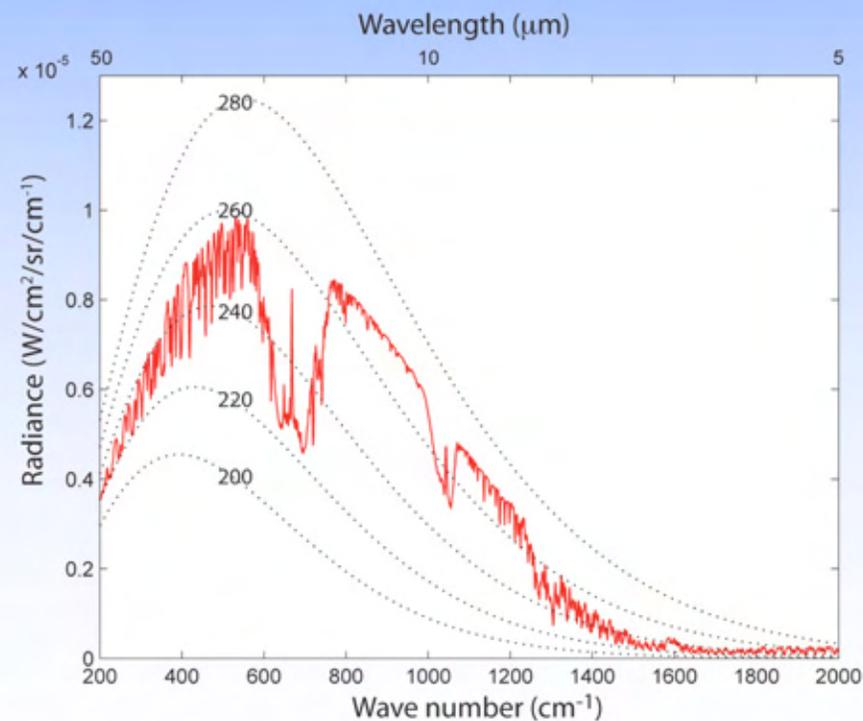
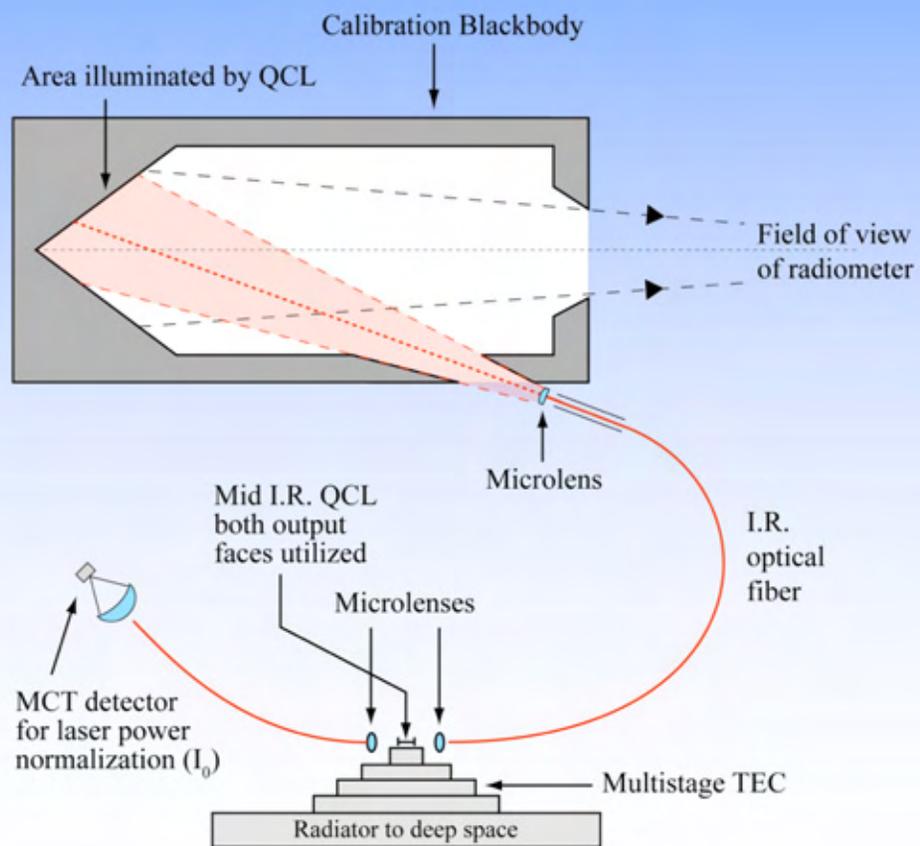
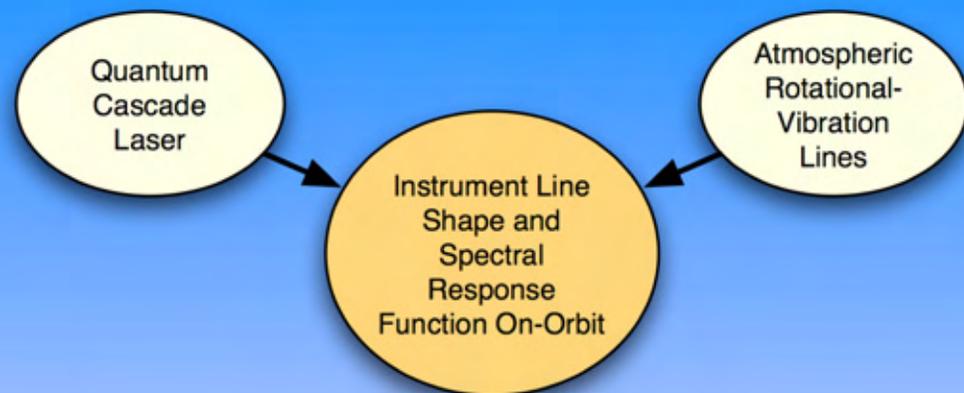
$$I_v(T) = \epsilon_{\text{AXIS}} B_v(T)$$

# Determination of Emissivity On Orbit: Heated Scene Tube

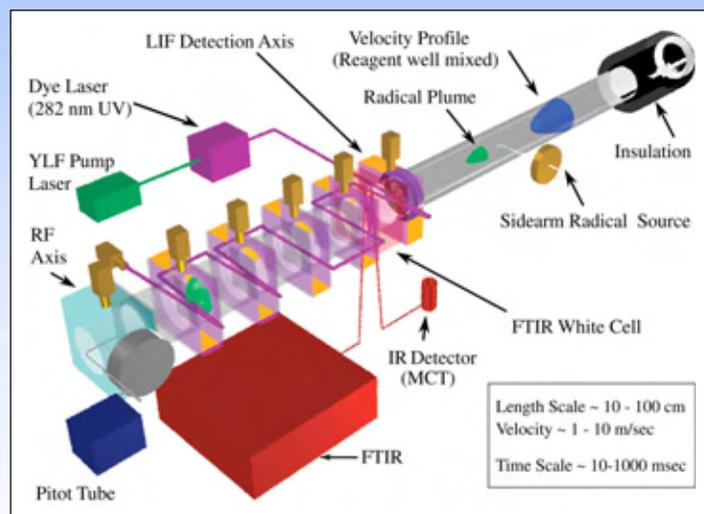
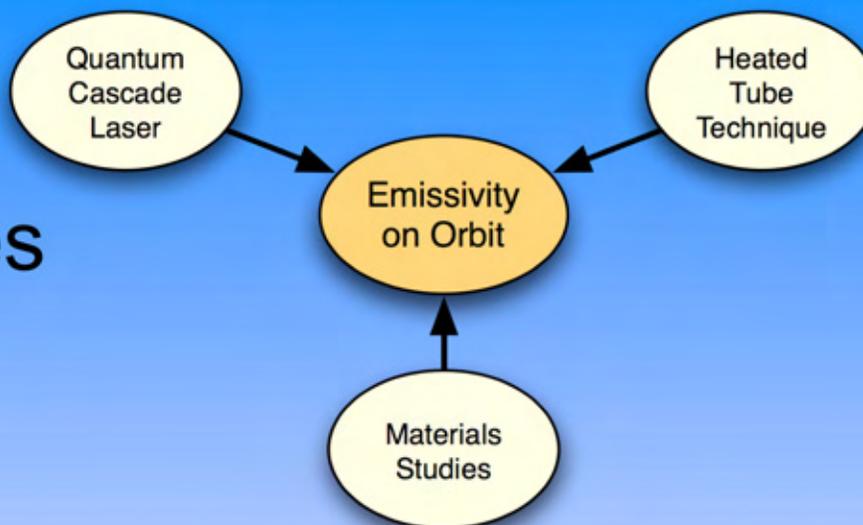


$$M_{instrument} = \underbrace{\varepsilon \cdot B(T_{bb})}_{\text{direct radiance from BB}} + (1 - \varepsilon) \cdot \underbrace{[F \cdot B(T_{tube}) + (1 - F) \cdot B(T_{bg})]}_{\text{reflected radiance from BB}}$$

# Instrument Line Shape and Spectral Response Function On Orbit: Quantum Cascade Laser and Atmospheric Rotation-Vibration Lines



# Emissivity On Orbit: Materials Studies

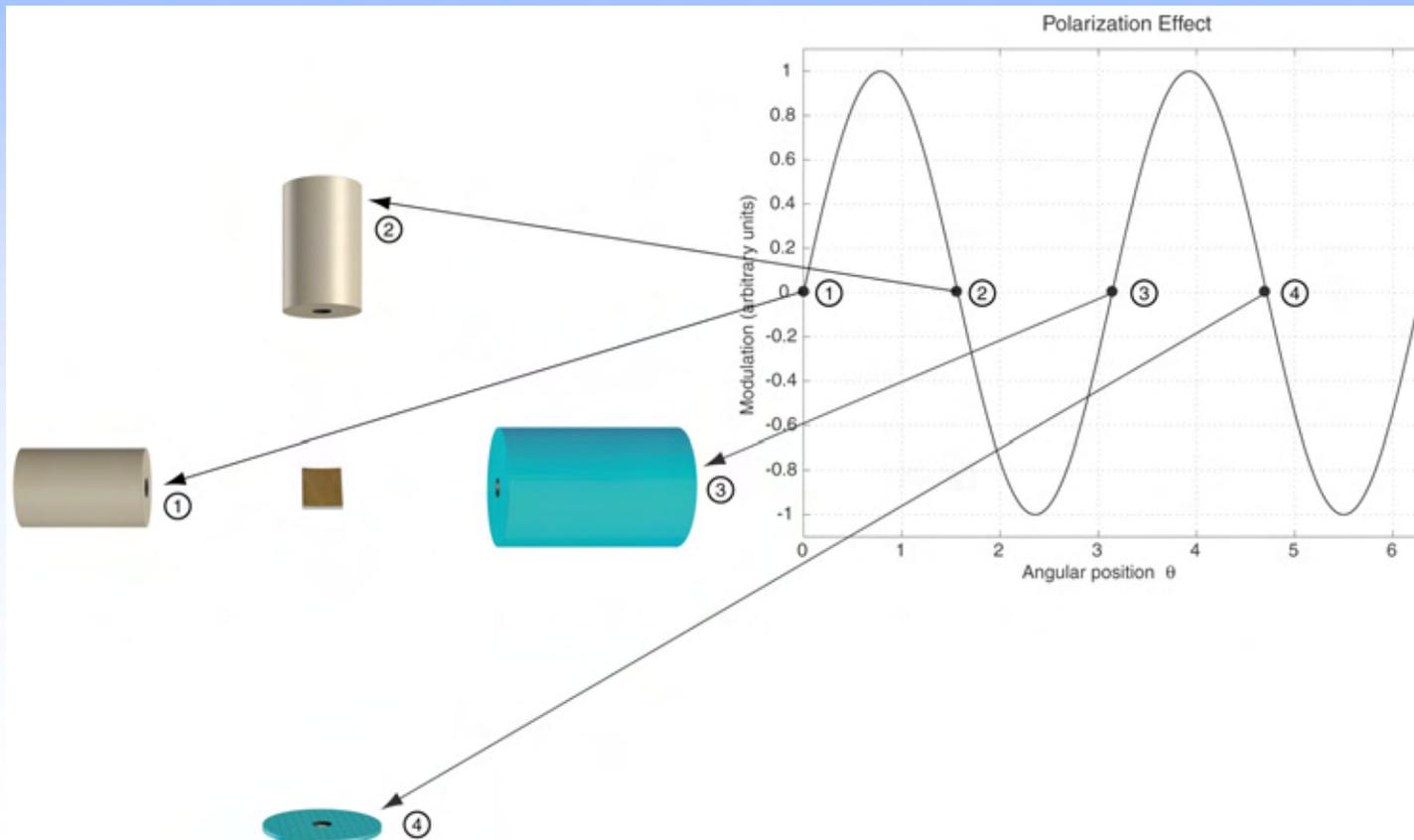


# PRIORITY: Polarization Determination

Rotation of scene selection mirror introduces polarization effect that modulates instrument gain

$$S = S_0 + \rho (S_0 - B) \cos 2\theta$$

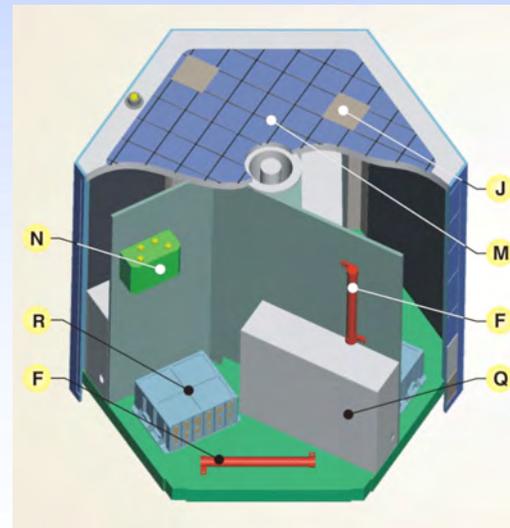
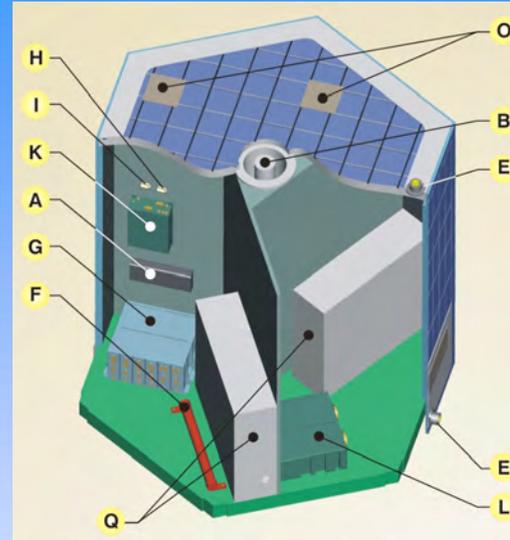
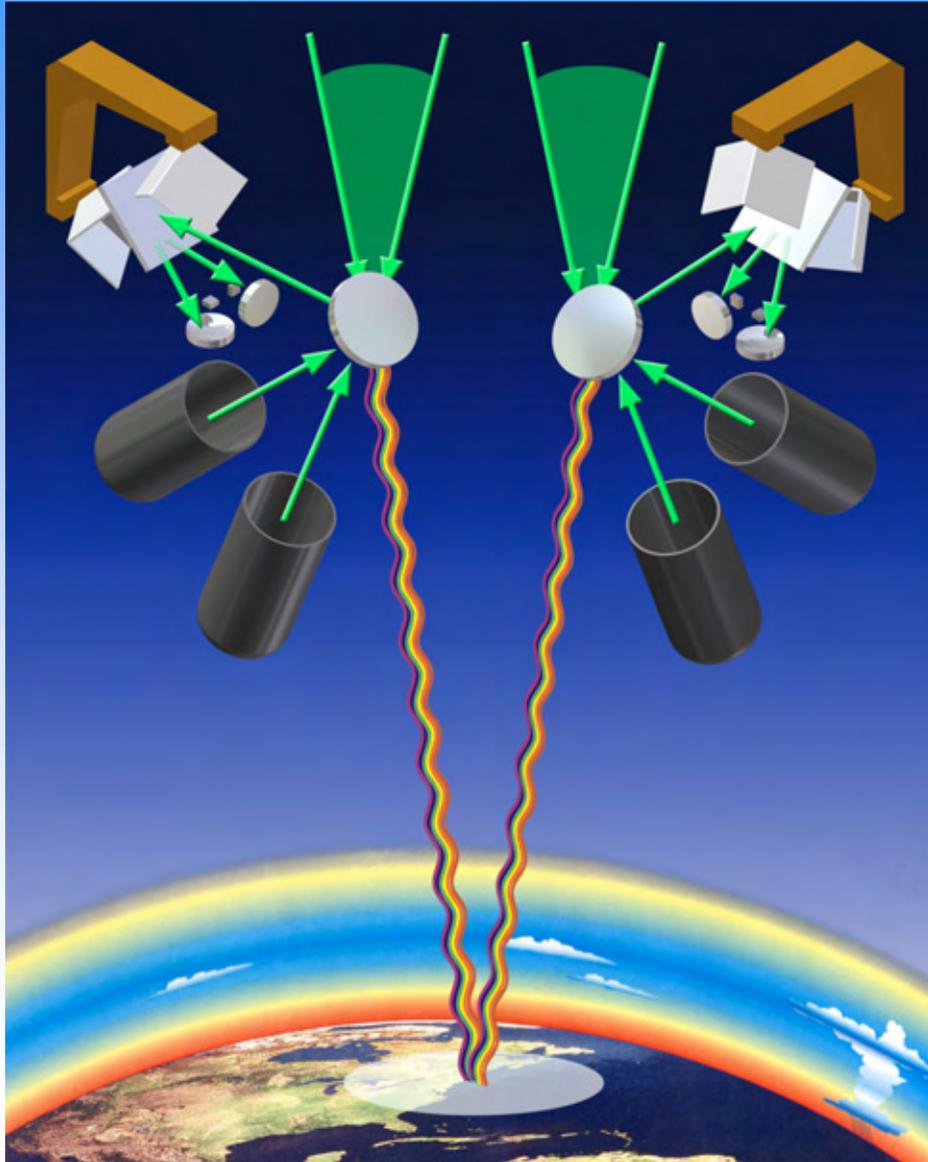
Observed signal  $S$  = Polarized radiance relayed by pointing mirror  $S_0$  + Amplitude of modulation from polarization  $\rho$  (Planck function at measured temperature of pointing mirror  $B$ )  $\cos 2\theta$  Angular position of mirror  $\theta$



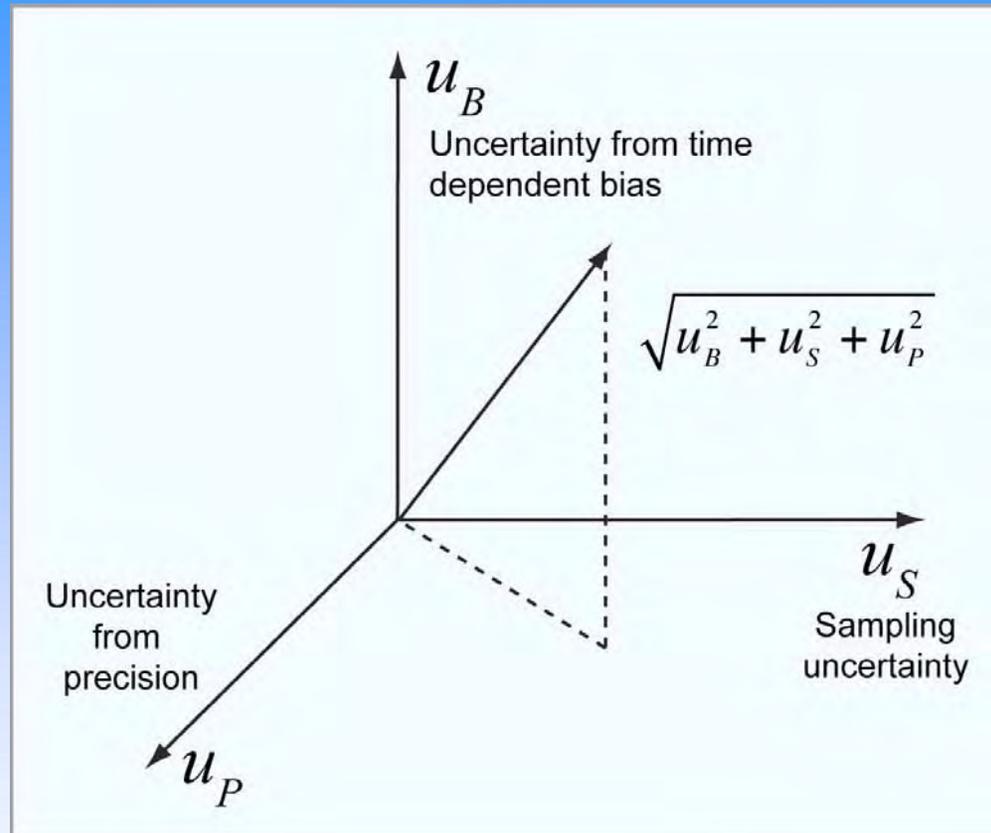
# What are the Advantages of the Fourier Transform Interferometer for climate studies?

- The ILS/SRF is defined over the entire instrument spectral window by two wavelength-independent properties: The maximum optical path difference (OPD) and the stable optical field stop geometry. This principle has been directly proven with laser ILS measurements during testing of CrIS for NPOESS, TES for NASA Aura, and IASI for METOP1.
- The spectral resolution required by climate requirements ( $1.0 \text{ cm}^{-1}$ ), the optical core of the interferometer, is both small and simple yet the product of entrance aperture area and solid angle of acceptance (the étendue) is large. This provides the ability to employ redundant interferometers needed to test for systematic errors on orbit.
- Because of its integrated laser based methodology system, the ILS/SRF for the Fourier transform spectrometer is insensitive to instrument geometry and does not require the extremely precise thermal control needed for a grating instrument.
- The FTS delivers very broad spectral coverage to a single detector resulting in a very simple optical, thermal, and detector configuration.

# The Multiple Interferometer



# Sampling: The Key to a Climate Strategy



- The recovery of climate averages with an uncertainty of  $0.1 \text{ K } 3\sigma$
- Recovery in the face of large diurnal and semi-diurnal amplitude, large variance resulting from weather “noise”.

# **Decadal Survey CLARREO Mission**

## **Sampling Issues and Intercalibration of Other Sounders**

CLARREO Workshop

17-19 July 2007

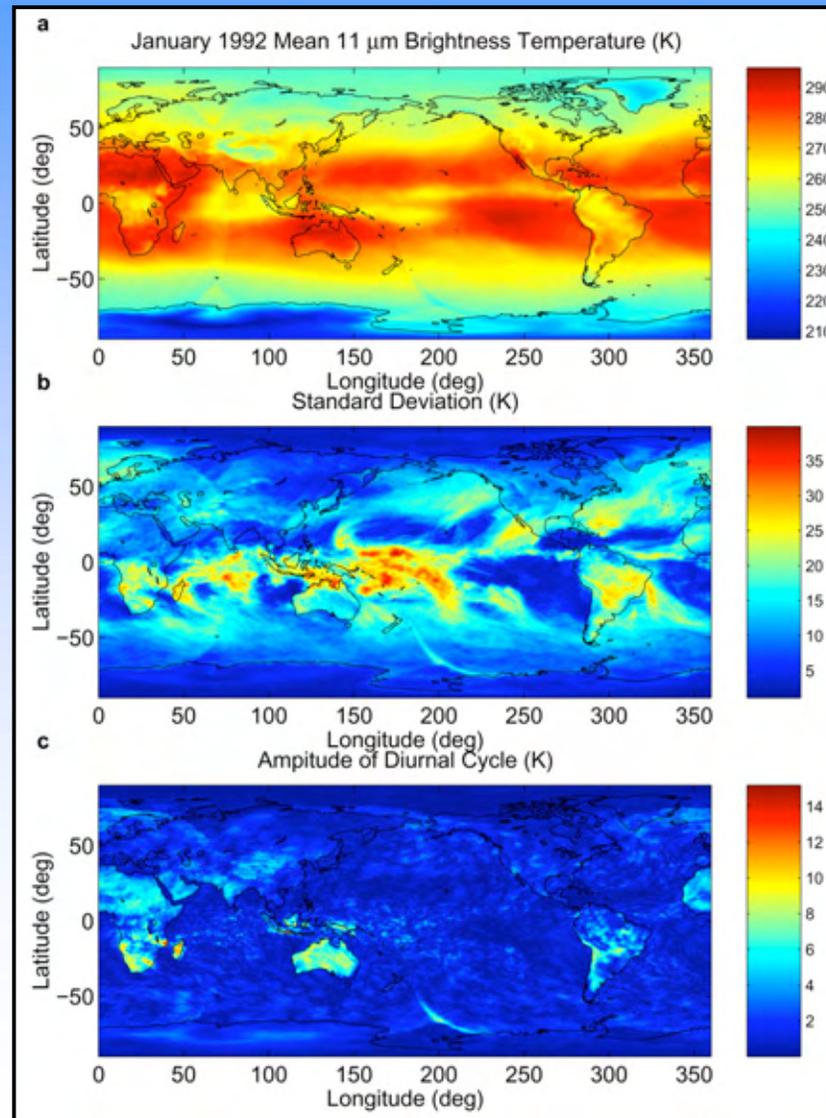
University of Maryland Inn and Conference Center

Adelphi, MD

# Original Work of D. Kirk-Davidoff

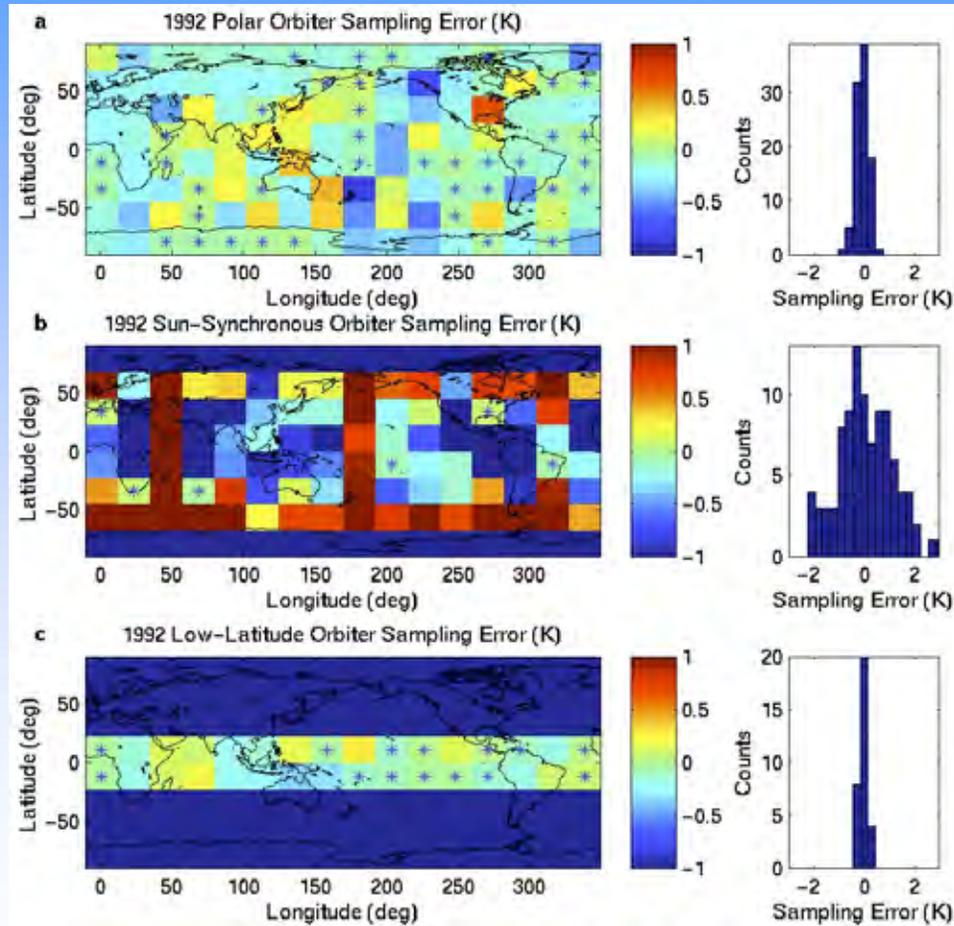
PRIORITY: Orbit Choice

Salby cloud imagery data at  $11\mu$

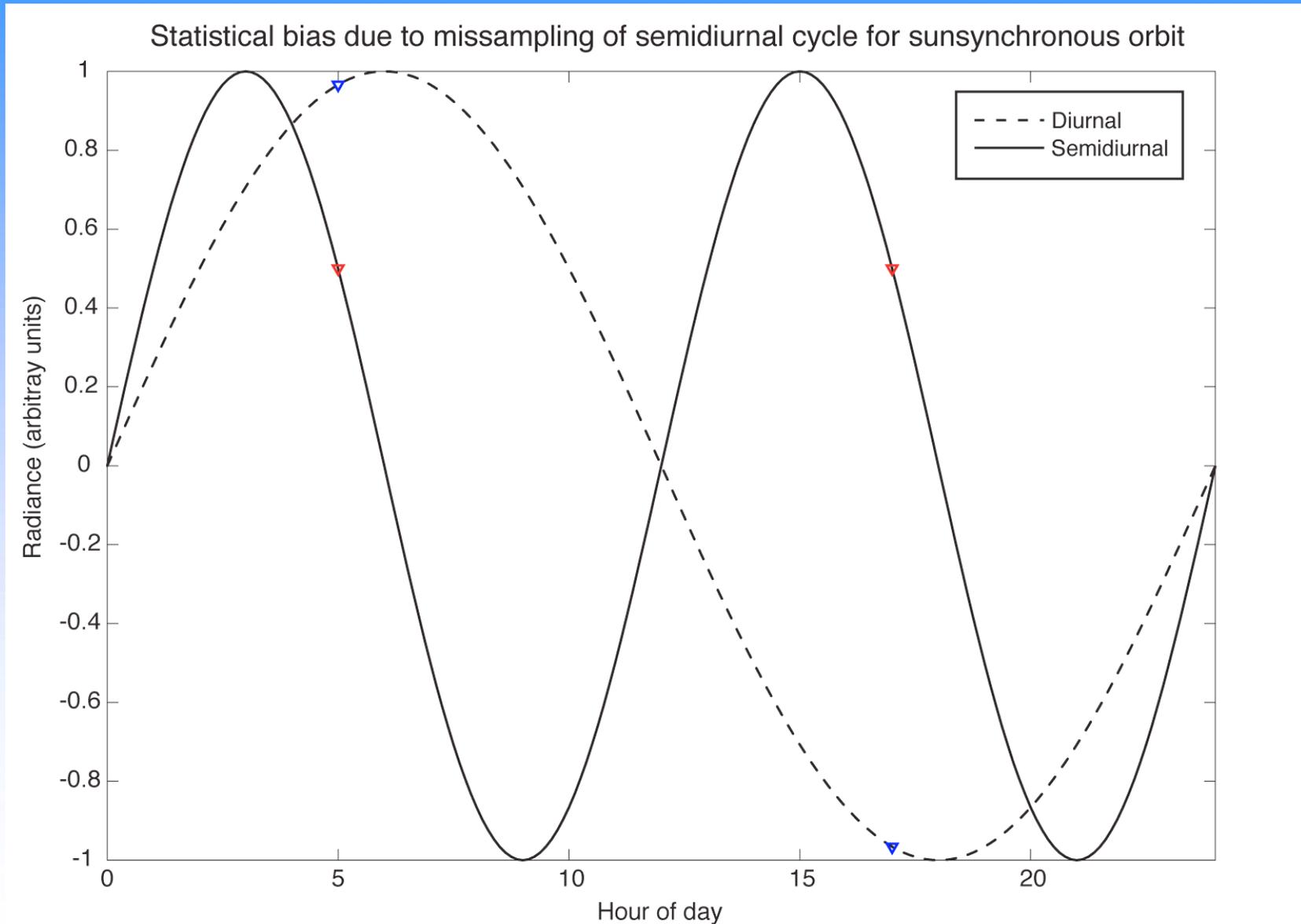


# Original Work of D. Kirk-Davidoff

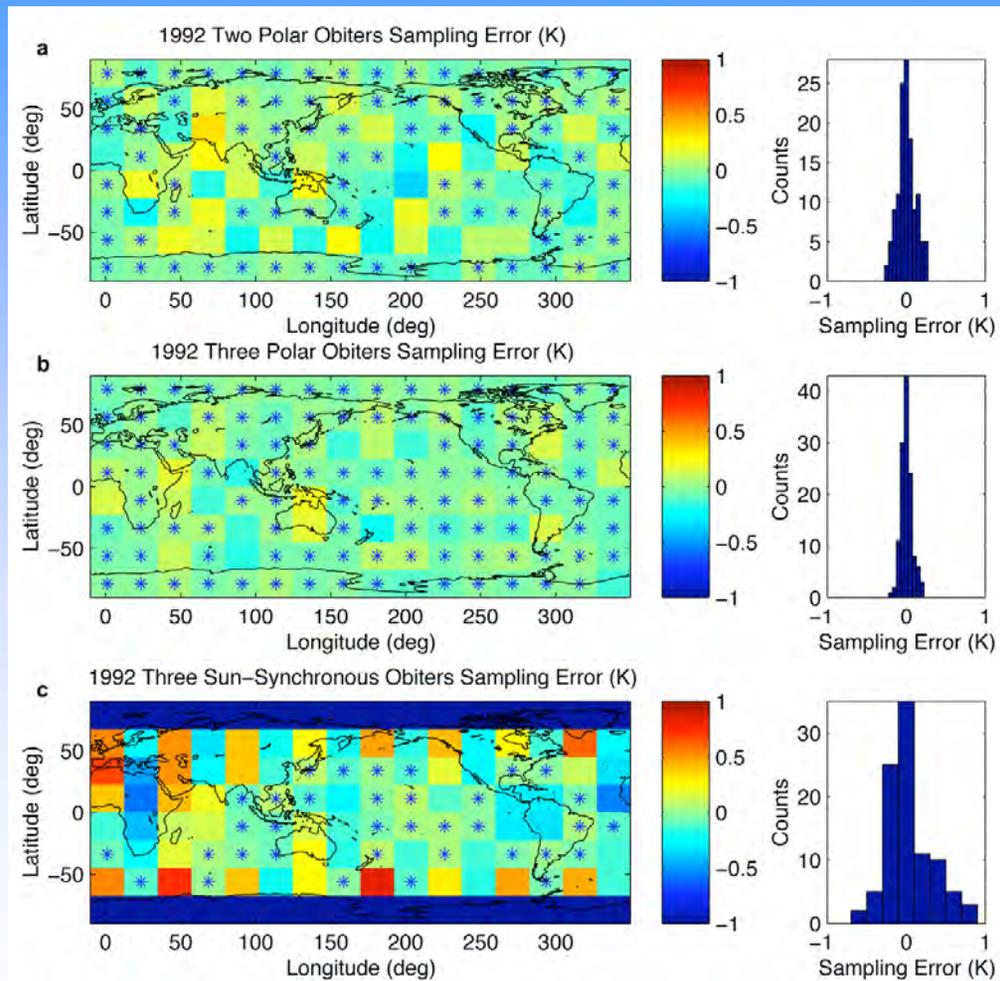
Comparison of 90° Polar Orbit, Sun-Sync Orbit, Low-Latitude Precessing Orbit

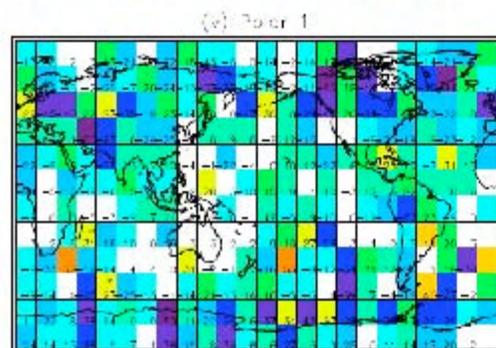
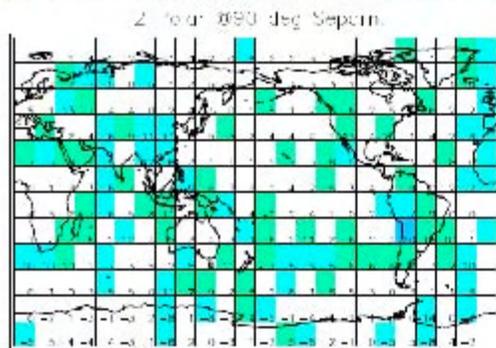
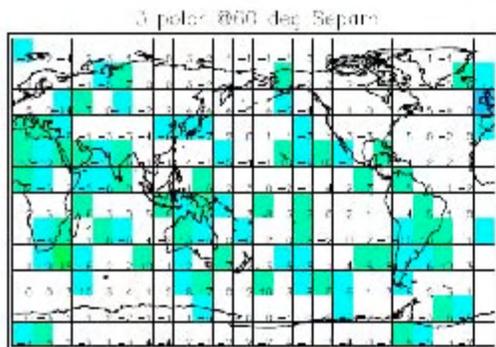


# Distinction Between Diurnal and Semidiurnal

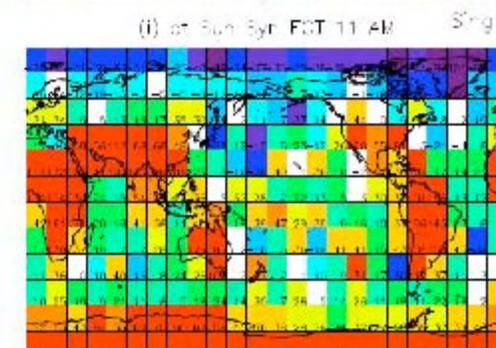
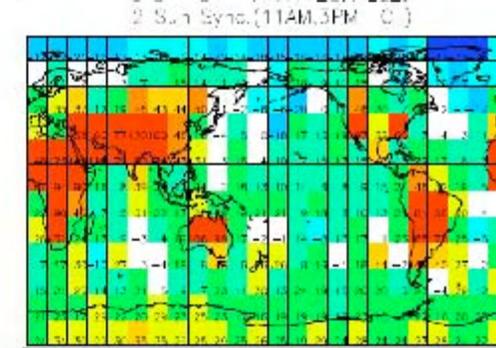
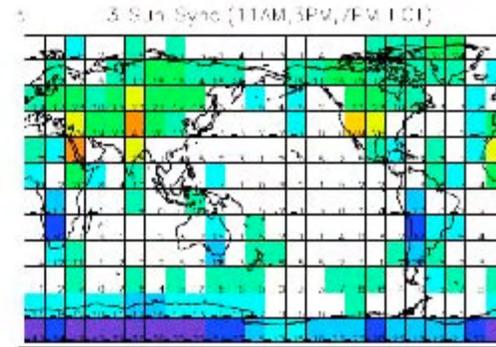
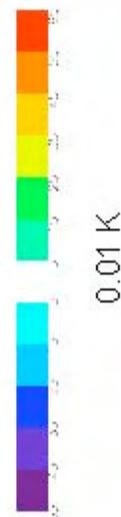


# Original Work of D. Kirk-Davidoff

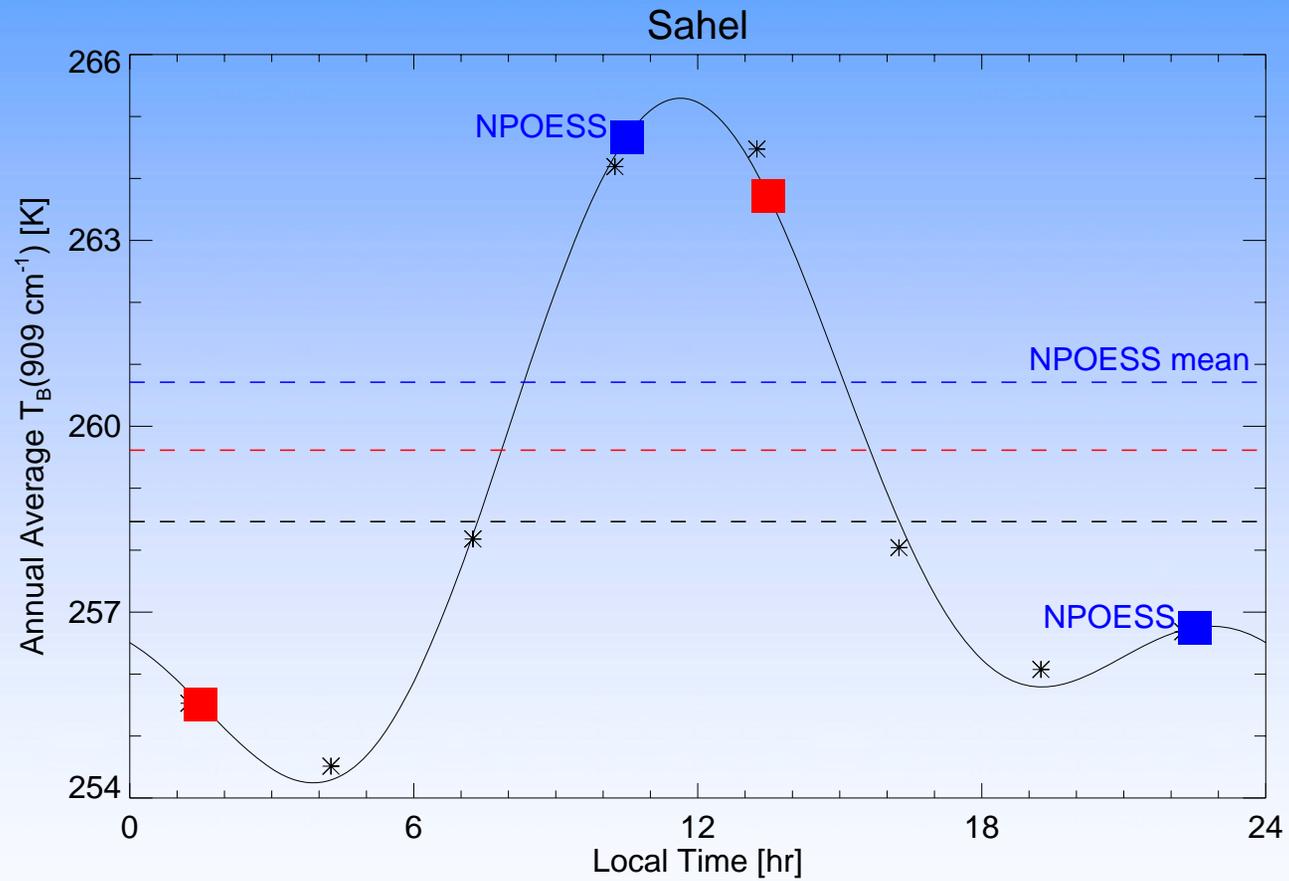




Sampling errors for  $90^\circ$  polar orbits (**left**) versus sun-synchronous orbits (**right**), for one, two or three satellites.

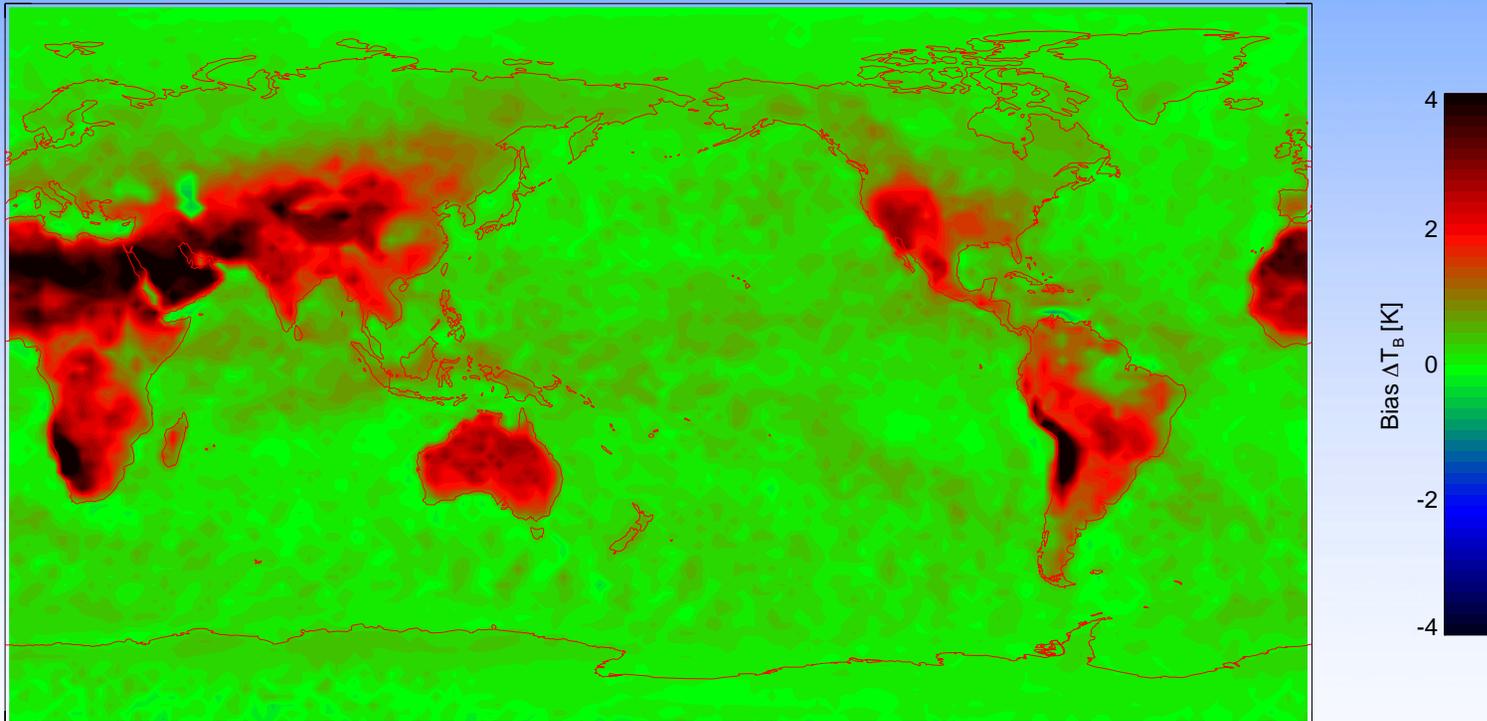


# Semidiurnal Cycle Bias (2)

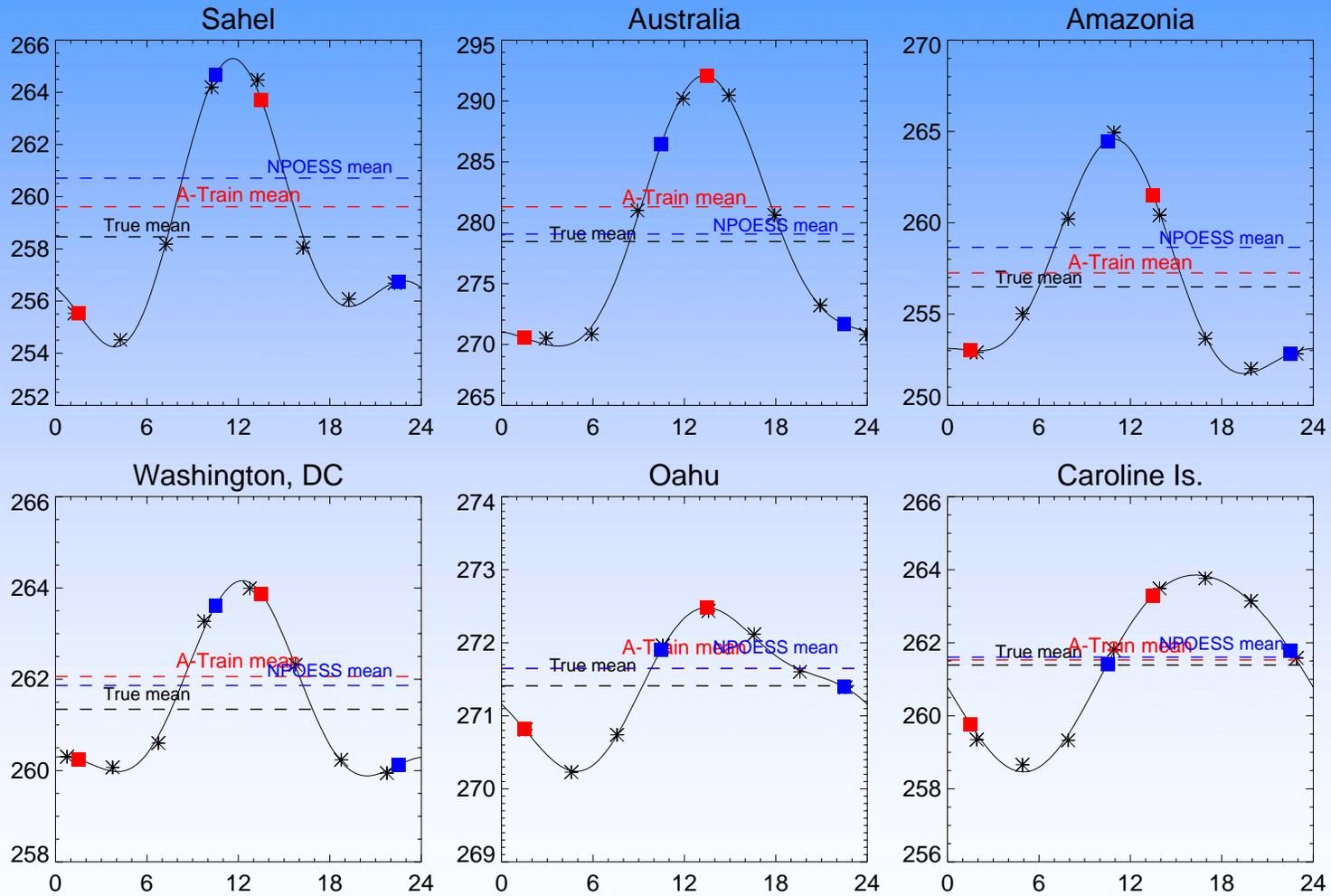


# Semidiurnal Cycle Bias (1)

Bias ( $909\text{ cm}^{-1}$ ) for 1:30 Orbit



# Bias Around the World



# Conclusion

- Semidiurnal component is a critical issue for climate benchmark
- Precessing is important, but the rate is not
- Three 90° polar orbits is key to global benchmark observation

Primary goal of CLARREO is to

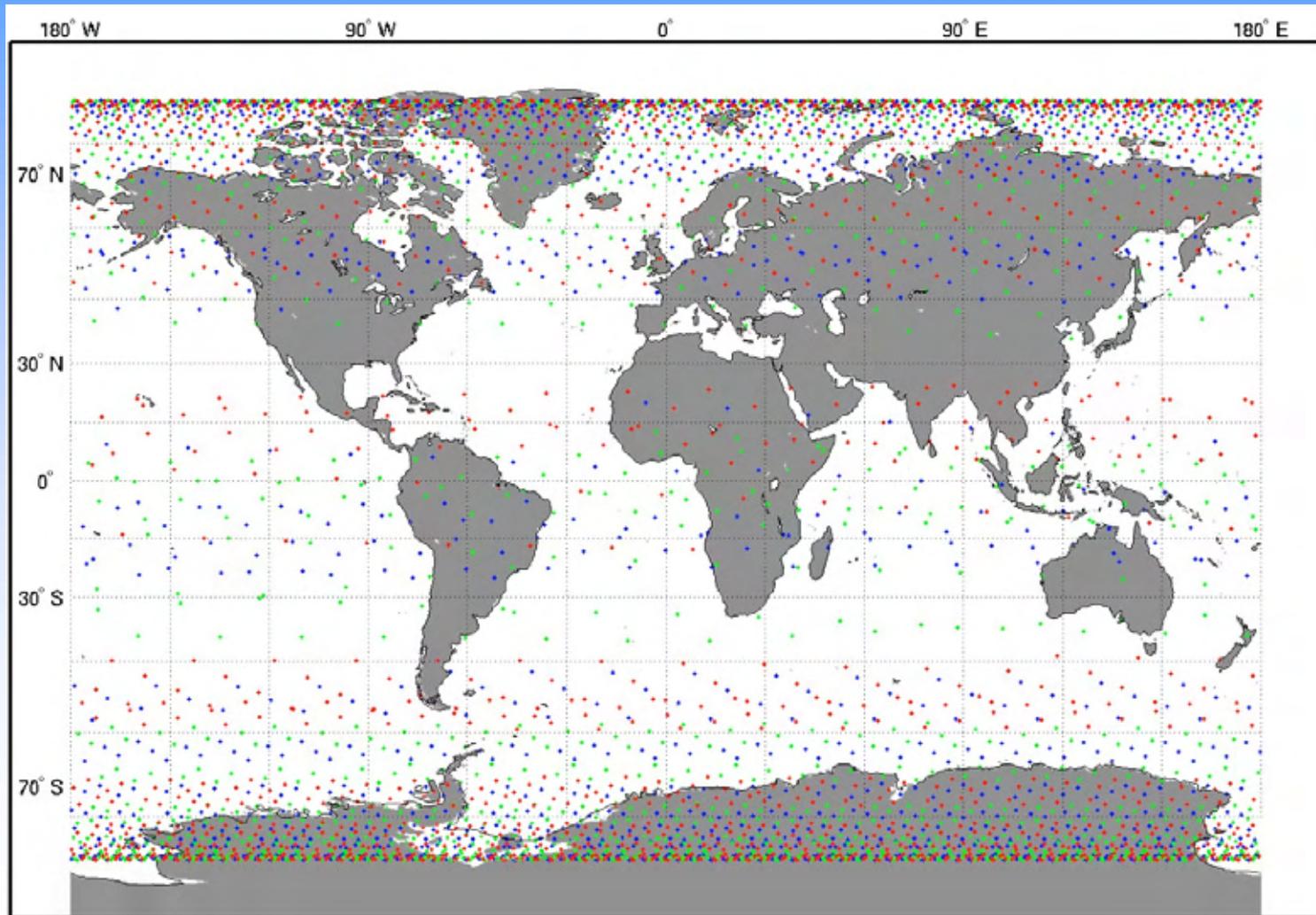
1. Establish the benchmark climate record
2. Systematically test climate forecast models

In addition, a secondary goal is to provide an on-orbit standard for the calibration of other infrared space-borne sensors.

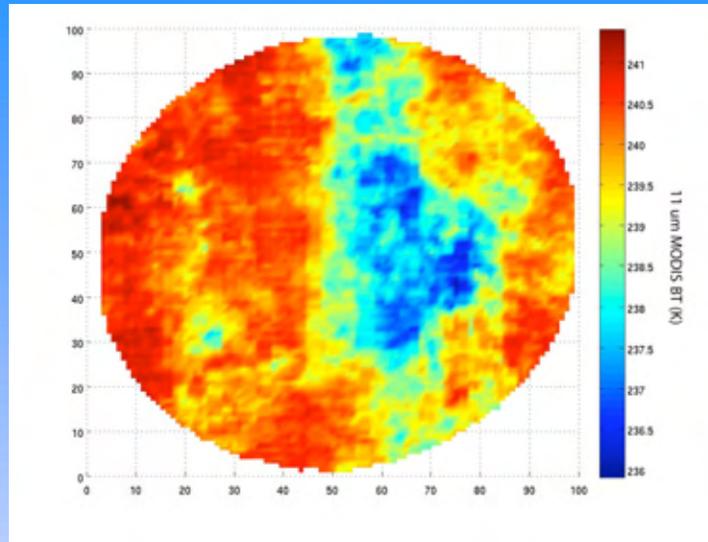
# Methodology

- Three 90-degree CLARREO orbits are simulated with their right ascension separated by 120 degrees.
- The geo-located intersections between simulated CLARREO and actual Aqua orbital tracks for the year of 2006 are identified. An intersection is defined to be an orbital crossing separated by no more than 15 minutes between CLARREO and Aqua.
- For each intersection CLARREO FOV within the 10 degrees of the nadir MODIS swath are identified for a range of CLARREO sampling frequencies
- For each CLARREO FOV a CLARREO 100 km surface footprint is simulated using measured MODIS 6.7, 11, and 14.2  $\mu\text{m}$  brightness temperatures (BT).
- The spatial sampling characteristics for both IASI and CrIS are super-imposed on the CLARREO footprint. The difference between the mean IASI/CrIS and CLARREO BT is then computed with the difference resulting from the IASI/CrIS sub-sampling the CLARREO footprint.
- The uncertainty resulting from the allowed 15 minute time difference between the orbital intersections is determined for each CLARREO FOV by off setting the center of CLARREO fov in the MODIS swath as function of time difference between the MODIS and CLARREO intersection time.

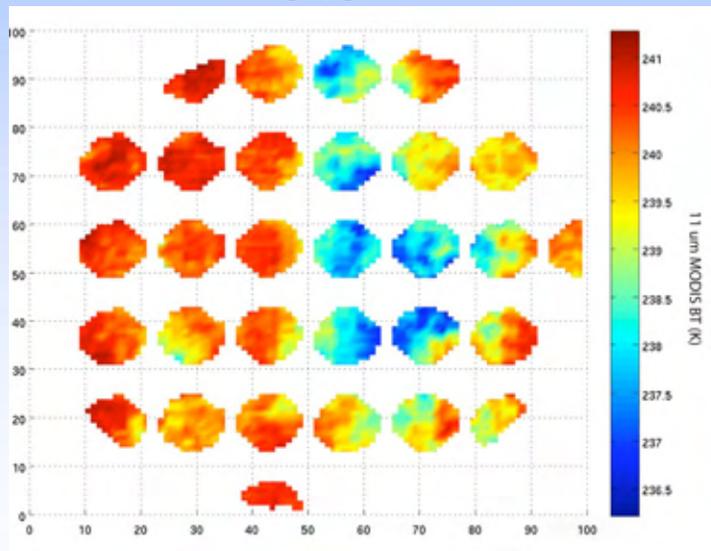
# Location of CLARREO and Aqua Orbital Intersections for Year 2006



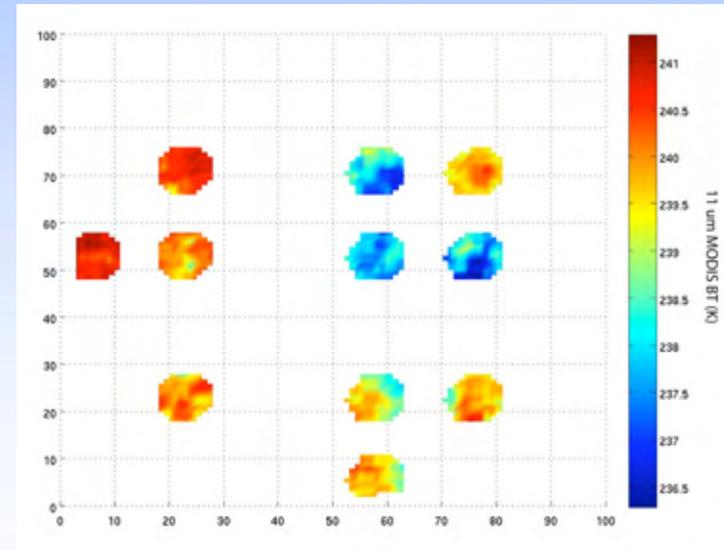
# CLARREO

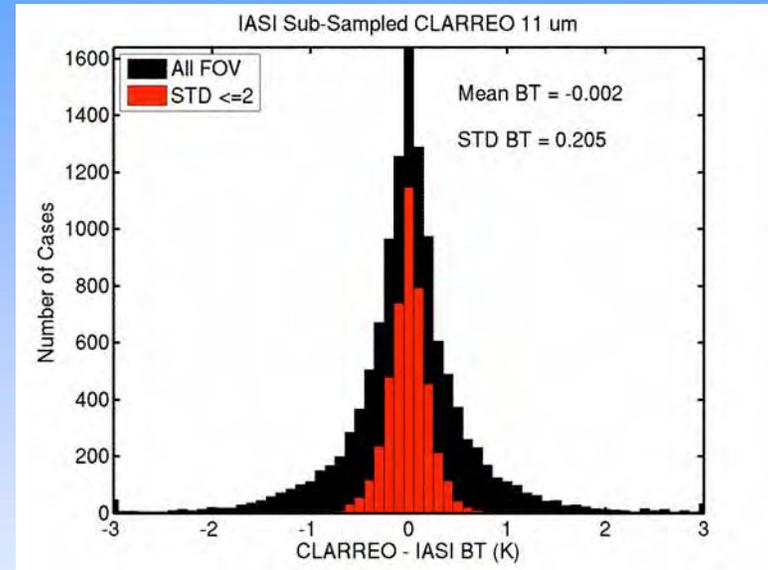
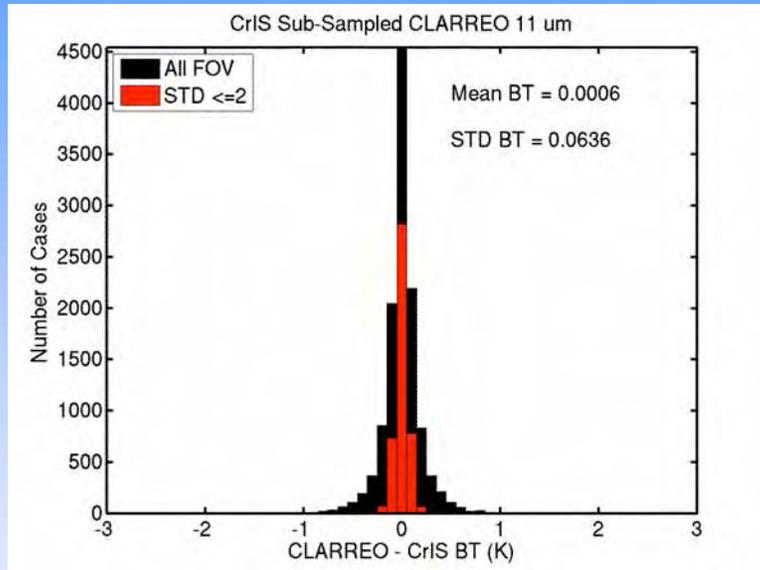


CrIS



IASI





# Summary of Conclusions

1. Using CLARREO FOVs with spatial standard deviations less than 3K, the uncertainty in the monthly mean brightness temperature differences (CLARREO minus IASI, CLARREO minus CrIS) due to differences in spatial and temporal sampling are less than 0.02 K.
2. To meet a monthly inter-calibration accuracy of 0.1 K  $3\sigma$ , the maximum allowable instrument noise for individual CLARREO FOV is approximately 0.6 K, with no assumed spectral averaging. This assumes single channel calibration with no noise filtering or spectral averaging and three CLARREO satellites with sampling frequency of 10 seconds
3. The number of usable monthly CLARREO Fields of view (BT STD < 2 K and 10 second sampling) during 2006 does not vary significantly by month with the number of FOV between 400–500. As result, the monthly CLARREO noise requirement (0.6 K) for intercalibration remains consistent during the year.

# Conclusions for Establishing the Benchmark Climate Record

- Orbits: Three  $90^\circ$  polar orbits spaced by  $60^\circ$  in orbital plane are recommended. This choice gives true global coverage and all local times are covered every two months, thereby minimizing diurnal sampling biases.
- The best strategy for the objective of intercalibrating of other IR sounders is to employ the three CLARREO IR/GPS satellites to establish the climate record, then establish the bias between CLARREO and the other sounders using SNO and Climate Target domains.

# **Decadal Survey CLARREO Mission**

## **Reflected Solar Irradiance**

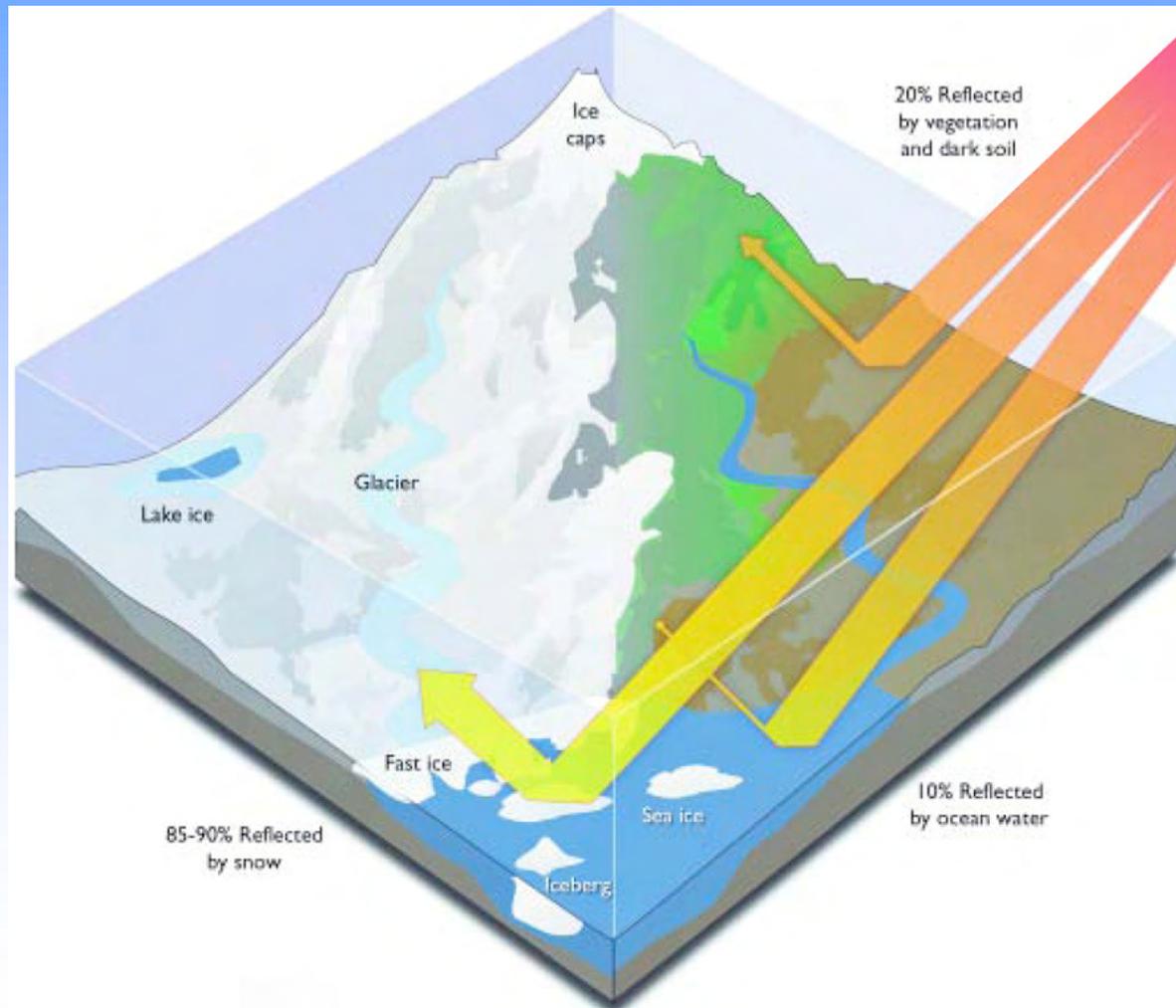
CLARREO Workshop

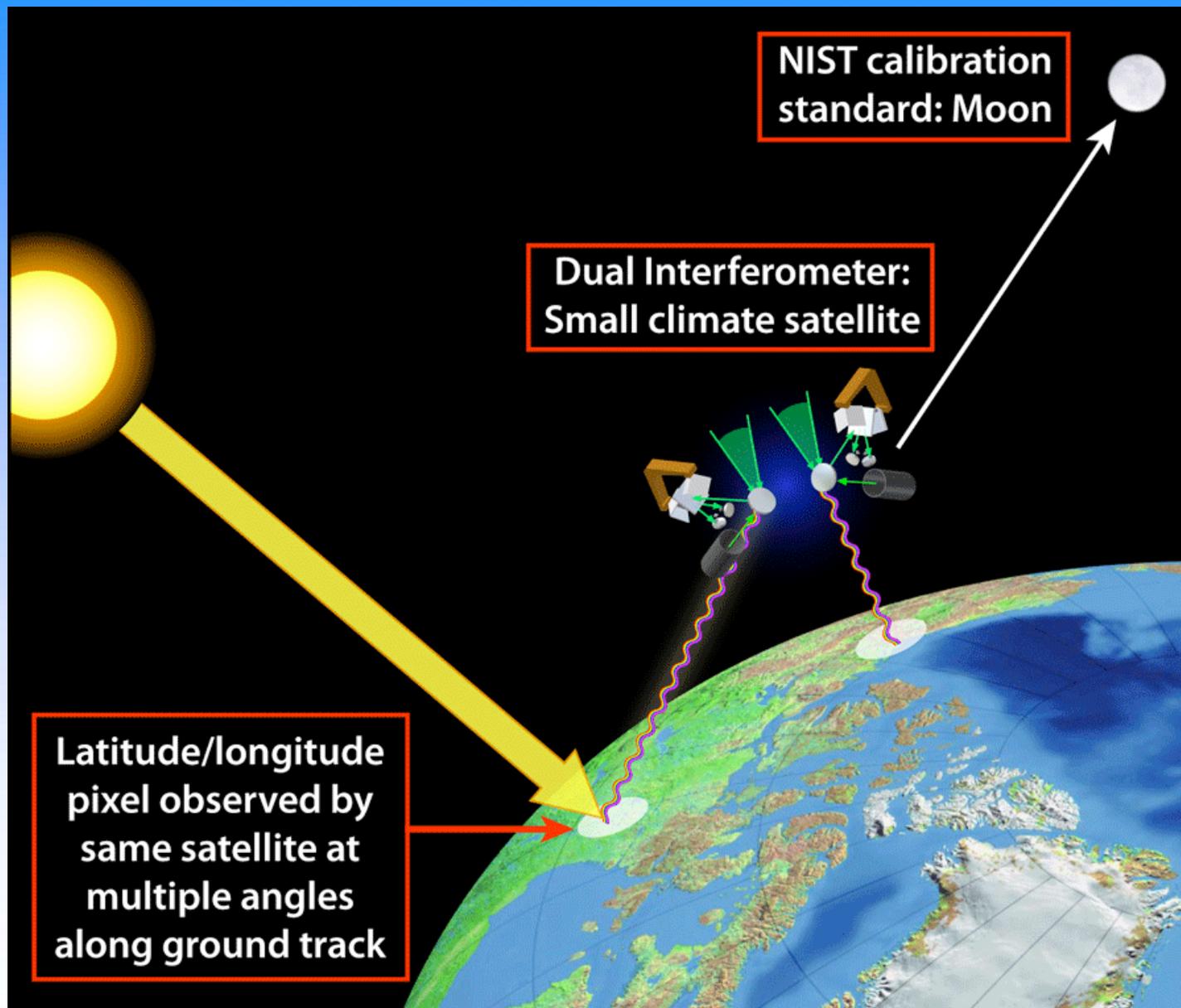
17-19 July 2007

University of Maryland Inn and Conference Center

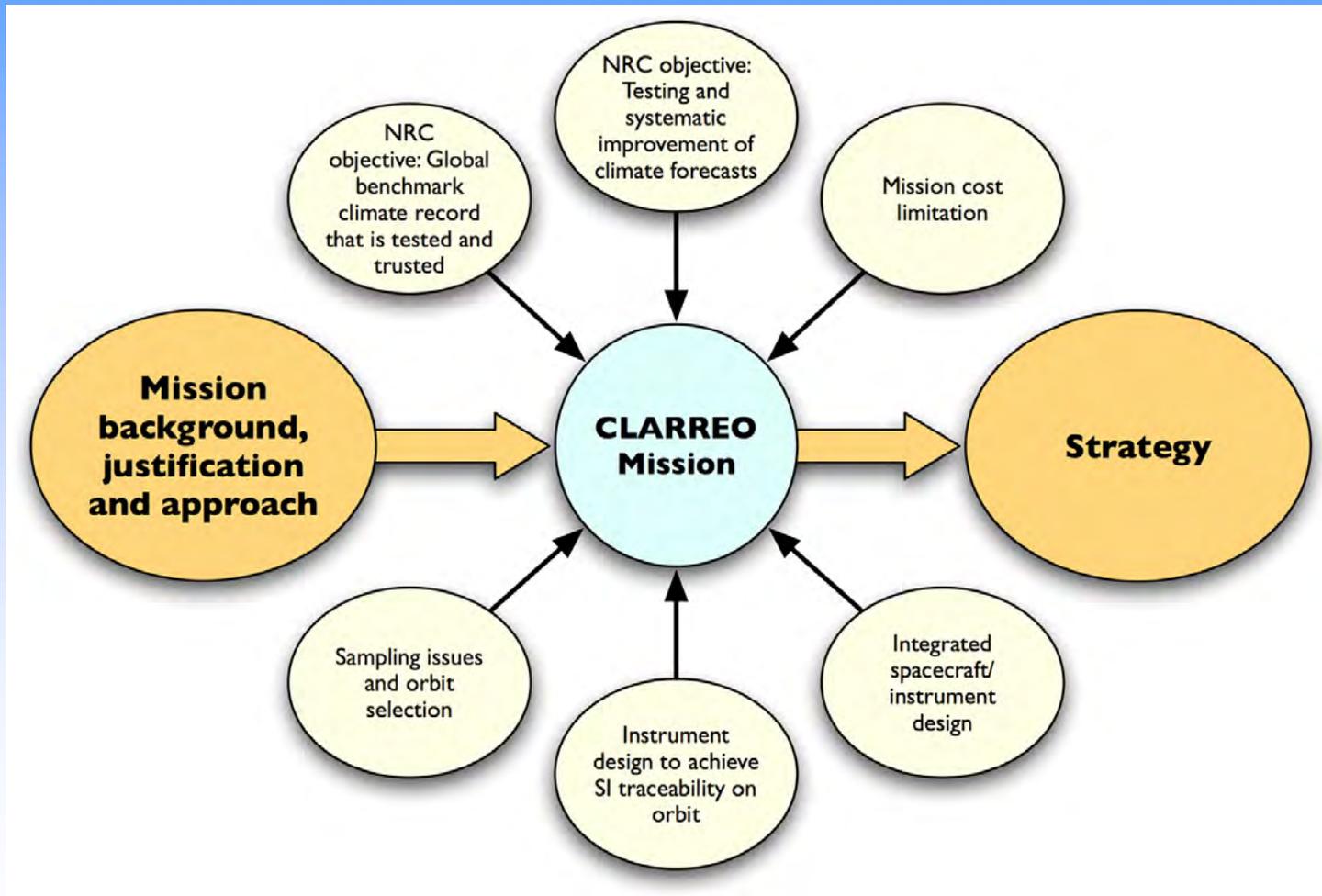
Adelphi, MD

# Planetary Albedo

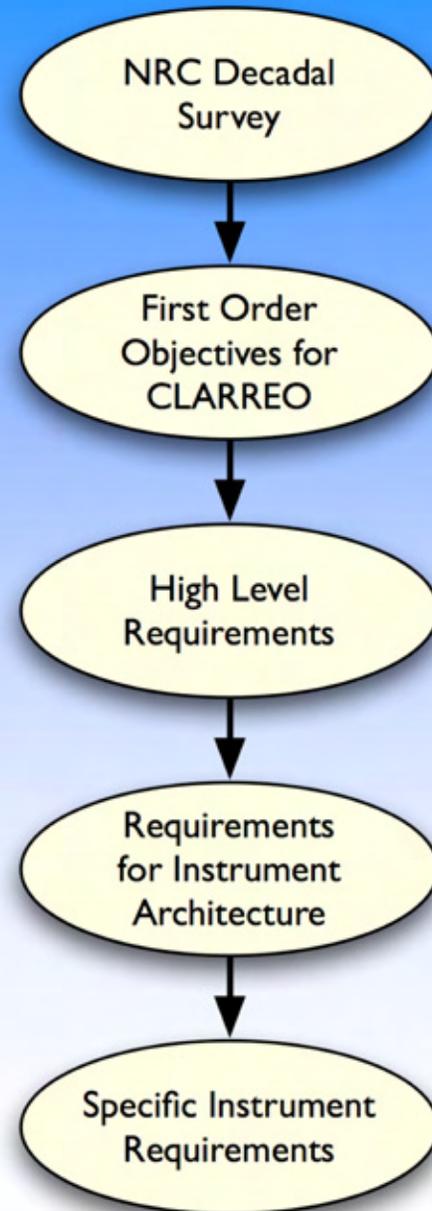




# Structure of CLARREO Presentation



# Conclusions



# Conclusions: First Order Objectives

- First order objective is to initiate a new generation of high accuracy, SI traceable on-orbit, climate benchmark measurements that will be continued in perpetuity, systematically improved and open for cross check and verification.
- A closely associated primary objective is the testing and systematic improvements of climate forecast models using a strategic balance between prioritization of new benchmark climate observations and mathematical tools that link those observations to climate forecast model testing.
- It is expected that by achieving high accuracy (absolute) and by a strategic combination of satellite orbits a combined measurement and sampling uncertainty ( $< 0.1 \text{ K } 2\sigma$  brightness temperature for  $15^\circ \times 30^\circ$  latitude/longitude regional, annual mean) that the long-term trend can be definitively separated from more rapid variations in the 10–20 year time frame.
  - The best strategy for the objective of intercalibrating of other IR sounders is to employ the three CLARREO IR/GPS satellites to establish the climate record, then establish the bias between CLARREO and the other sounders using SNO and Climate Target domains.

# Conclusions: High Level Requirements

- An implicit requirement is to make this long-term global benchmark climate record affordable, and therefore to strive for simplicity.
- High level requirements for consideration at the workshop include:
  - Orbits: Three 90° polar orbits spaced by 60° in orbital plane are recommended. This choice gives true global coverage and all local times are covered every two months, thereby minimizing diurnal sampling biases.
  - Achievement of SI traceability (absolute) on-orbit: Redundant and fully independent determination of each variable of quantitative significance to the error budget dictates the selected instrument architecture and the choice of independent on-orbit observations.
  - For the separation of climate forcing and response—critical both for the climate record and for systematic testing of climate forecasts—absolute spectrally resolved radiance in the thermal infrared and GPS radio occultation constitute the foundation of the benchmark climate record.

# Conclusions: Requirements for Instrument Architecture

- SI traceable, absolute calibration on orbit, by the logic of fundamental metrology, requires the determination of systematic error on-orbit. Determination of systematic error in turn requires an independent determination of each term in the error budget. For the determination of absolute spectrally resolved radiance in the thermal infrared this requires:
  - Redundant spectrometers on-orbit to reveal systematic errors
  - Absolute thermometry such as the phase transition of an element embedded in multiple blackbodies for each spectrometer
  - Direct determination of blackbody emissivity
  - Direct determination of instrument line shape applicable across the spectrum
  - Direct measurement of instrument polarization
  - Detector chain linearity determination
  - Foundation of continuous calibration of flight subsystems against NIST primary infrared standards and evaluation of flight blackbodies in NIST facilities

# Conclusions: Specific Instrument Requirements

- **Spectrometer Design:** Fourier transform spectrometer. This requirement follows from the need for simplicity, broad nyquist sampled spectral coverage, redundant spectrometers on the same spacecraft, instrument line shape determination across the full spectrum, polarization determination.
- **Spatial Footprint and Angular Sampling:** Order of 50-100 km, nadir viewing only
- **Spectral Resolution and Sampling:** Order 1  $\text{cm}^{-1}$  with nyquist sampling across interferogram
- **Spectral Range:** 200-3000  $\text{cm}^{-1}$  the spectrum coverage is meant to include broad coverage of key parts of the infrared spectrum that contain significant information about the state of the atmosphere and that can be observed with high accuracy.
- **Pointing Accuracy and Knowledge:** Within  $5^\circ$  of nadir;  $< 0.1^\circ$  uncertainty
- **Temporal Resolution and Sampling:**  $< 15$  sec resolution and  $< 60$  sec intervals

# Conclusions: Specific Instrument Requirements (continued)

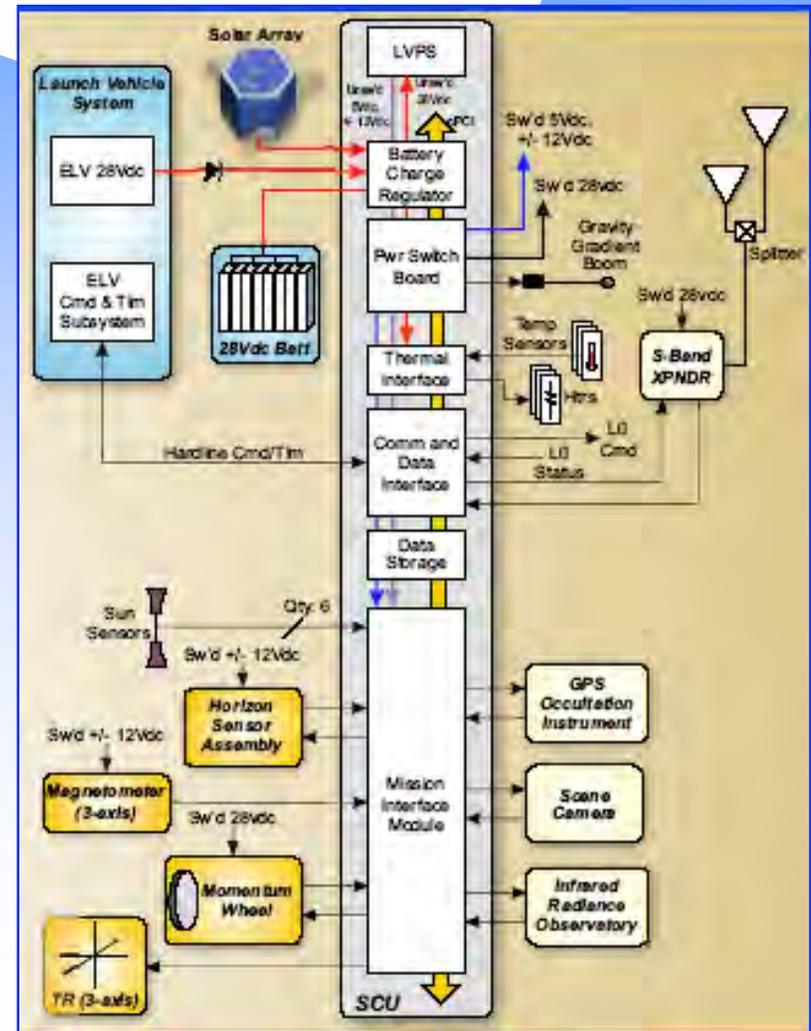
- **Detectors:** Chosen to meet NE $\Delta$ T requirements with high level of linearity. Unlike most applications, detector sensitivity is not a major issue for this application. Many samples will be averaged, making noise requirements reasonably easy to achieve using pyroelectric detectors for 200 to 1200  $\text{cm}^{-1}$ , photovoltaic MCT for 650 to 2000 and sandwiches InSb from 1825  $\rightarrow$  3000  $\text{cm}^{-1}$
- **Blackbody Design:** Two blackbodies for each spectrometer, plus deep space view. Each blackbody equipped with phase transition cells for a range of absolute temperatures and direct emissivity measurements on-orbit. One of the blackbodies would be a warm blackbody references ( $\sim$  300 K); one would be a variable temperature with a range 200-320 K.
- **On-Orbit Performance Characterization:** Absolute temperature, cavity emissivity, instrument line shape, linearity, polarization, stray light

# CLARREO Spacecraft Concept



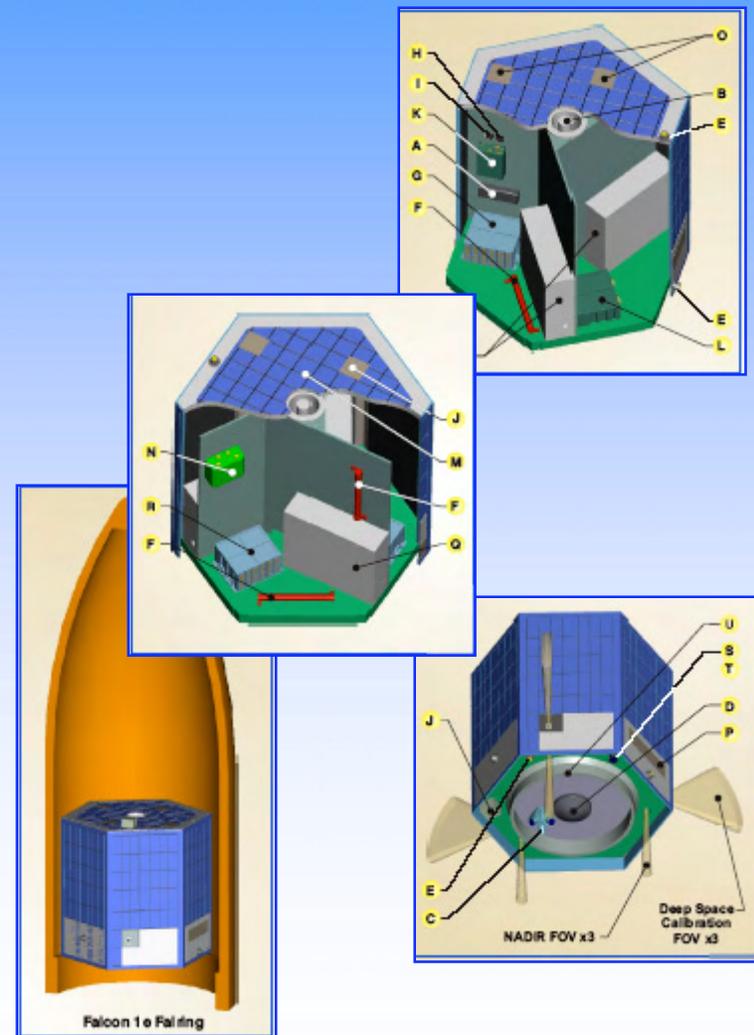
- **Launch and Orbit**
  - SpaceX Falcon 1e
  - 750km circular, 90deg inclination
  - 30krad TID
- **Mechanical**
  - 122cm-dia x 129cm (launch) Al honeycomb
  - 124.7kg
  - Passive thermal control
  - Isolated Instrument interface
- **Electrical Power**
  - 255W rigid body mount S/A
  - 10.5A-hr Li-ion battery
- **Communication and Data**
  - 16MIP computer
  - 512Mbyte data storage
  - S-band CCSDS 2.5Mbps data downlink
- **Attitude**
  - Knowledge: 0.2deg GPS with Horizon Sensor, Mag, CSS backup
  - Control: Gravity gradient pitch/roll with momentum biased yaw

All EPS, CDS, and ADCS components have flight heritage



# Robust Margins Exist In All Subsystems

- Mechanical
  - Fairing volume margin
    - 27% (girth)
    - 36% (non-tapering height)
  - 217% launch mass margin
- Electrical Power
  - 27% (EOL) Power Margin
  - 13.2% (EOL) Battery DOD
- Communication and Data
  - 7.5dB Science downlink margin
  - 26.4dB Status downlink margin
  - 44.4dB Uplink margin
  - 24hr data storage margin
- Attitude
  - 0.2deg knowledge (3-axis)
  - 1.5deg control (3-axis)
- Fault Protection
  - Gravity-gradient stabilized
  - Full body S/A (nadir exception)
  - Selective redundancy in ADCS, thermal, and power



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